0000573412

RF/ER-95-0096.UN

ADMIN RECORD

1994 Well Evaluation Report for the Rocky Flats Environmental Technology Site Final

March 1995

Volume I
Text

EG&G ROCKY FLATS

EG&G Rocky Flats, Inc.
P.O. Box 464
Golden, Colorado 80402

TABLE OF CONTENTS

Page

VOLUME I

TABLE OF CONTENTS--Continued Page

VOLUME I--Continued

TABLE OF CONTENTS--Continued Page

VOLUME I--Continued

TABLE OF CONTENTS--Continued Page

VOLUME I--Continued

TABLE OF CONTENTS--Continued Page

VOLUME I--Continued

TABLE OF CONTENTS--Continued Page

VOLUME I--Continued

TABLE OF CONTENTS--Continued Page

VOLUME I--Continued

LIST OF TABLES

TABLE OF CONTENTS--Continued

Page

VOLUME I--Continued

LIST OF TABLES--Continued

LIST OF FIGURES

TABLE OF CONTENTS--Continued

Page

VOLUME I--Continued

LIST OF FIGURES--Continued

VOLUME II

LIST OF APPENDICES

TABLE OF CONTENTS--Continued Page

VOLUME II--Continued

LIST OF APPENDICES--Continued

TABLE OF CONTENTS--Continued

Page

VOLUME III

LIST OF APPENDICES--Continued

VOLUME IV

Acronym	Explanation
A	Amps
AEC	Atomic Energy Commission
Am	Americium
APHA	American Public Health Association
ASCII	American Standard Code for Information Interchange
ASTM	American Society for Testing and Materials
B	Laboratory Qualifier for: **Inorganics** - reported value is less than contract-required detection limit, but greater than instrument detection limit. **Organics** - analyte found in associated blank as well as in sample.
bgs	Below ground surface
°C	Degrees Celsius, degrees Centigrade
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CLP	Contract Laboratory Program
cm/sec	Centimeters per second
cm	Centimeter
CO_2	Carbon Dioxide
CO_3	Carbonate
Cs	Cesium
DGI	Dynamic Graphics Incorporated
DO	Dissolved Oxygen
DOE	Department of Energy
DTG	Draft Technical Guidance
ERPD	Environmental Restoration Program Division
EPA	Environmental Protection Agency
ER	Environmental Restoration

Acronym	Explanation
ERDA	Energy Research and Development Administration
°F	Degrees Fahrenheit
Fe	Iron
FERMC	Fernald Environmental Restoration Management Corporation
FO	Field Operations
ft/day	Feet per day
ft	Feet
FTU	Formazin Turbidity Units
gals	gallons
GMP	Groundwater Monitoring Program
GPMPP	Groundwater Protection and Monitoring Program Plan
GT	Geotechnical
GW	Groundwater
HCO_3	Bicarbonate
Hz	Hertz
I/O	Input/Output
ID	Internal Diameter
IGWMC	International Ground Water Modeling Center
IHSS	Individual Hazardous Substance Site
in	Inches
ISE	Ion-specific electrode
ISO	International Standards Organization
IT	International Technology (Corporation)
J	Laboratory Qualifier for organics - value is estimated, either for a TIC or when a compound is present (spectral identification criteria are met, but the value is <CRQL)
°K	Degrees Kelvin

Acronym	Explanation
K_d	Distribution Coefficient
KCl	Potassium Chloride
L/min	Liters per Minute
LCD	Liquid Crystal Display
LED	Light-emitting diode
LSD	Least Significant Digit
mbar	Millibar
mg/L	Milligrams per liter
mL	Milliliter
ml/min	Milliliters per Minute
Mn	Manganese
mS/cm	MilliSiemens per Centimeter
mV	Millivolts
N	Nitrogen
N_2	Nitrogen Gas
N_2O	Nitrous Oxide
NA	Not Applicable or Not Available
NH_4^+	Ammonium
NIOSH	National Institute for Occupational Safety and Health
nm	Nanometer
No.	Number
NO_2^-	Nitrite
NO_3^-	Nitrate
NS	Not Specified
NTU	Nephelometric Turbidity Units
OU	Operable Unit
PCE	Tetrachloroethylene
pCi/L	picoCuries per liter
pg	Page

Acronym	Explanation
ppm	Parts per million
ppt	Parts per trillion
psi	Pounds Per Square Inch
psig	pounds per square inch, gauge
Pu	Plutonium
PVC	Polyvinyl Chloride
QC	Quality Control
rpm	Revolutions per minute
RCA	Radiologically Controlled Area
RCRA	Resource Conservation and Recovery Act
RFEDS	Rocky Flats Environmental Database System
RFETS	Rocky Flats Environmental Technology Site
RSKERL	Robert S. Kerr Environmental Research Laboratory
SCFM	Standard Cubic Feet per Minute
SO_4	Sulfate
SOP	Standard Operating Procedures
Sr	Strontium
SS	Stainless Steel
TAL	Target Analyte List
TCE	Trichloroethylene
TCL	Target Compound List
TDS	Total Dissolved Solids
TIC	Tentatively Identified Compound
TMA	TherMo Analytical (Corporation)
TOC	Total Organic Carbon
TOX	Total Organic Halogens
TSS	Total Suspended Solids
μg/L	Micrograms per liter
μS/cm	MicroSiemens per Centimeter

Acronym	Explanation
U	Uranium
U	Laboratory Qualifier for inorganics and organics - compound was analyzed for, but not detected
USGS	United States Geological Survey
V	Volts
VOC	Volatile Organic Compound
WARP	Well Abandonment and Replacement Program
WER	Well Evaluation Report
WIG	Wax-impregnated graphite
WWE	Wright Water Engineers

EXECUTIVE SUMMARY

An evaluation was performed with the purpose of assessing various elements of the groundwater monitoring well network at the Rocky Flats Environmental Technology Site (RFETS). The evaluation focused on specific issues related to improving the methodologies for collecting field data. The specific tasks completed and the conclusions that were drawn are detailed below.

A. An evaluation of field parameter measurements was conducted. Existing RFETS methodologies for the measurement of field parameters were evaluated with the goal of improving the quality of the field parameter data. This task involved literature searches, interviews with outside sources, and the field testing of commercially available field parameter instrumentation, including flow cells and multiparameter field instrumentation. The conclusions resulting from the evaluation included:

- Multiparameter instruments for measuring field parameters will equal or exceed the performance of the instrumentation currently used in RFETS groundwater monitoring program.

- Flow cells were shown to be an improvement over the current method of monitoring field parameters in that no handling or transfer of purge or sample water is necessary. This results in less sample turbulence and little or no air contact. Consequently, the data quality of both the field measurements and the laboratory analytical results are likely to be enhanced. The use of flow cells allows real-time monitoring and recording of data, enhancing the reliability and consistency of the field measurements. Flow cells require the use of downhole pumping systems.

B. Methods to reduce sediment in wells were analyzed. One aspect of the analysis was the evaluation of methods for aseptic borehole drilling. The conclusions are:

- Isolation of surface soils from lower portions of a borehole is best accomplished by scraping approximately six inches from the ground surface and using a surface casing to minimize contact of downhole drilling equipment with surface soils.

- Isolation of potentially contaminated zones at depth is best accomplished using telescoping well construction.

Another aspect of this task was the evaluation of well development methods. The goal was to make recommendations for improvements to development activities based on the review of literature. The conclusion is:

- Given the typical fine-grained texture and low productivity of the saturated zones at RFETS, it is unlikely that completely effective development is possible in some wells. The most effective means to minimize the impacts to sampling is to continue the current practice of low energy pumping or bailing combined with optimal well screen and sandpack installations. In addition, low flow dedicated pump systems should be used to purge and sample which will minimize sample turbidity.

A third aspect of the task was to compare low flow sampling methods with current RFETS methods. A field evaluation was conducted that included purging and sampling using low flow methods, bailing, and dedicated pump systems. An additional goal of the evaluation was to minimize the volume of required purge water and reduce the aeration of the groundwater samples collected. The conclusion is:

- Low flow purging and sampling is an effective and improved method compared to the current RFETS method of bailing wells. Wells that historically produced water with turbidity greater than 1,000 nephelometric turbidity units (NTU) using bailers to purge and collect samples produced turbidity values below 5 NTU using the low flow method. Once field crews gained experience in using the pumps, purge volumes needed to attain field parameter stability were generally less than one gallon, contrasted to the three well volume purging of five to six gallons required with bailers.

C. Recovery rates for wells at RFETS were monitored and tabulated. Post-sampling water level recovery was monitored in the 194 RFETS wells that are also currently used for monthly water level measurements. The objective was to obtain data to estimate the effective recovery period required to allow collection of complete analytical suites. The data can also be used to schedule the water level measurements in order to ensure the timely measurement of static water level conditions.

- Results include water level data collected using dataloggers, and graphs of the data showing the amount of well recovery needed to obtain the necessary volumes for the various analytical suites and to attain 90 percent recovery.

D. Groundwater flow modeling was conducted to generate a hypothetical flow model for use in siting future groundwater monitoring wells at RFETS. A 10-year simulation was conducted.

- Results of the analysis identified 13 locations for potential additional monitoring wells.

1.0 INTRODUCTION

Groundwater monitoring at the Rocky Flats Environmental Technology Site (RFETS) dates from the initial installation of groundwater wells in 1960 (EG&G - Rocky Flats, Inc. [EG&G], 1993b). The current monitoring network consists of 655 wells and piezometers (and 117 abandoned wells and piezometers) to meet the requirements of specific Department of Energy (DOE) orders, and federal and state environmental laws (Wright Water Engineers [WWE], 1993).

Results of work completed in 1994 for the annual Well Evaluation Report (WER) are presented in this report. Previous WERs have focused on other aspects of the Groundwater Monitoring Program, including a study of the wells appropriate for inclusion in the monitoring well network, and an assessment of the applicability of analytical suites to regulatory requirements. The 1994 WER focuses on:

- Field data collection methodologies with the goal of collecting more accurate field parameter data and improving the quality of analytical results;
- Evaluation of methods to reduce sediment in wells;
- Monitoring groundwater recovery rates in wells; and,
- Groundwater flow path analysis to assist in siting new wells.

1.1 Purpose of Report

Methods of well construction, development, purging, and sampling have evolved to comply with the increasingly sophisticated field methods required for accurate and representative laboratory measurement of groundwater chemistry. Methods currently used at RFETS have historically been viewed as adequate. However, EG&G Environmental Restoration (ER) has undertaken a wide-ranging evaluation of current and potential field methods and technologies to improve the quality of data collected in the Groundwater Monitoring Program. The following specific tasks were performed:

- Evaluate existing RFETS methodologies for the measurement of field parameters with the objective of improving the quality and validity of the data;
- Evaluate methods to reduce sediment in monitoring wells, including an evaluation of aseptic drilling methods, well construction design and installation, well development techniques, and alternative well purging and sample collection methods;
- Monitor and tabulate the results of post-sampling water level recovery in selected monitoring wells;
- Develop a site-wide groundwater numerical flow-path model to identify potential locations for additional monitoring wells; and;
- Present recommendations for improvements to current RFETS field methodologies related to the various tasks described above.

1.2 General Approach Taken

The general approach taken in the 1994 WER addresses the activities listed in the previous section, including the following steps:

- A compilation and review of literature related to field parameter measurements and methods to lessen sediment volumes entering the wells;
- An evaluation of current RFETS procedures and methodologies;
- Field and office evaluations of current procedures and alternative methodologies; and,
- Presentation and interpretation of the results of the evaluations, and discussion of the recommendations based on the results.

The literature review consisted of analyses of: regulatory agency guidance and requirements, industry standards, and published technical studies and investigations. The literature review focused specifically on the methods of field parameter measurement and techniques for decreasing sediment entering in wells. The list of references compiled for the literature review is presented in Section 9.0.

The discussion of current procedures and methodologies is based on Standard Operating Procedures (SOPs) detailed in the *Environmental Management Department* (EMD) *Operating Procedures, Volume I Field Operations* (FO), *Volume II Groundwater* (GW), and *Volume III Geotechnical* (GT) (EG&G, 1994d). Citations for specific procedures are provided in the relevant sections of this report.

Instruments for measuring field parameter and methods for well sampling were evaluated in the field to assess the relative merits of the alternative equipment and methods identified during the literature review as practical and worthy of closer scrutiny.

Data generated from the evaluations are discussed in the text and are provided as appendices to this report. Conclusions and recommendations are presented based on the consideration of both qualitative judgements and the quantitative results of the evaluations.

1.3 Organization of the Report

The 1994 Well Evaluation Report is organized as follows:

Section 1.0 ***Introduction*** - presents the project objectives, describes the operational history of RFETS, and summarizes the existing Groundwater Monitoring Program.

Section 2.0 ***Site Conditions*** - summarizes the geologic and hydrogeologic conditions at RFETS.

Section 3.0 ***Field Evaluation*** - describes the selection of wells, instruments, and pumping systems evaluated in the field program.

Section 4.0 ***Evaluation of Field Parameter Measurement*** - discusses existing RFETS methodologies for the measurement of field parameters, a literature review of the state of knowledge for field parameter measurement, and methods and results of a field evaluation of current and alternative field measurement methodologies and technologies.

Section 5.0 ***Evaluation to Methods to Reduce Sediment in Wells*** - discusses aseptic drilling methods, monitoring well design and installation, and methods for well development, and purging and sampling. Included are literature reviews and a methodology and results discussion.

Section 6.0 ***Monitoring of Recovery Rates in Selected Wells*** - describes the methods and results of monitoring water level recovery in wells following quarterly sampling.

Section 7.0 ***Groundwater Flow Path Analysis*** - presents the methods used and results obtained in developing a theoretical groundwater flow path analysis computer model to assess the adequacy of well locations in the current groundwater monitoring network, and propose new well locations, at RFETS.

Section 8.0 ***Summary of Conclusions and Recommendations*** - provides a quick reference of conclusions and recommendations developed from this work.

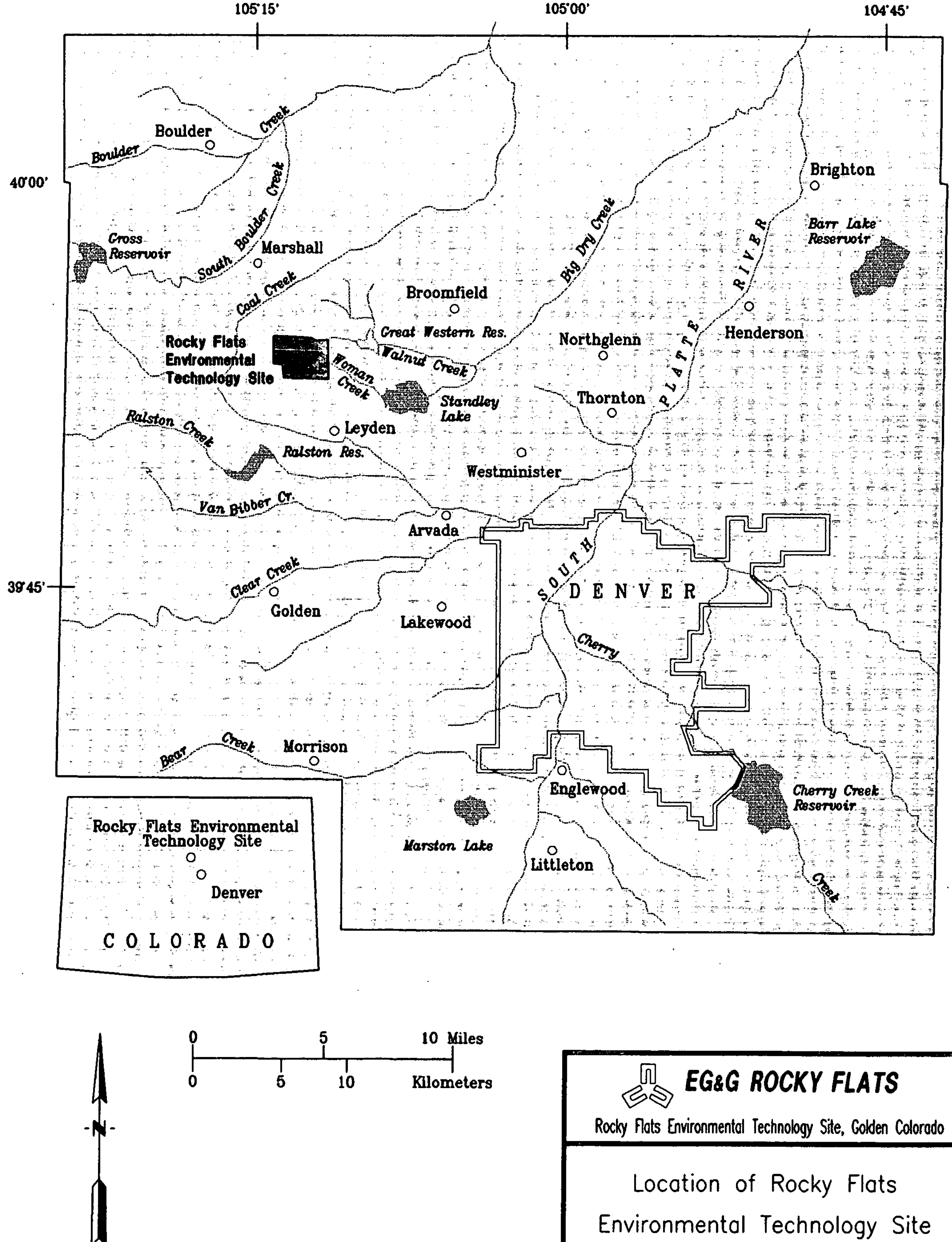
Section 9.0 ***References*** - lists references cited.

1.4 Facility Background and Plant Operations

Facility background and plant operations information presented in this section were obtained from the 1993 *Final Well Evaluation Report* (EG&G, 1994b) and the 1993 *Groundwater Protection and Monitoring Program Plan* (EG&G, 1993b).

RFETS is a government-owned, contractor-operated facility that was part of the nationwide nuclear weapons complex. RFETS is located approximately 16 miles northwest of Denver in northern Jefferson County, Colorado (Figure 1-1), and covers approximately 6,550 acres of land in Sections 1 through 4, and 9 through 15 of Township 2 South, Range 10 West of the 6th principal meridian. An Industrial Area occupies the central 400 acres of RFETS and contains the majority of the buildings on site. Surrounding the Industrial Area is a Buffer Zone of approximately 6,150 acres. The current Groundwater Monitoring Program encompasses both the Industrial Area and Buffer Zone.

RFETS was operated for the Atomic Energy Commission (AEC) from the facility inception in 1951. The AEC was dissolved in January, 1975, at which time, responsibility for the Plant was assigned to the Energy Research and Development Administration (ERDA). The ERDA was responsible for the facility until January, 1977, when it was succeeded by the Department of Energy (DOE). Dow Chemical USA was the prime operating contractor of the facility from 1951 through June 10, 1975. Rockwell International became the prime operating contractor on July 1, 1975, and served in that



EG&G ROCKY FLATS

Rocky Flats Environmental Technology Site, Golden Colorado

Location of Rocky Flats Environmental Technology Site

Well Evaluation Report

DATE : MARCH 1995	FIGURE : 1-1

Job No / Dwg No: TEMP / 2715A009
Last Update: 05:02p 27-Jun-95

capacity until December 31, 1989. The current operating contractor, EG&G-Rocky Flats, Inc., assumed operational responsibilities on January 1, 1990.

Until 1992, the facility was operated as a nuclear weapons research, development, and production complex. The plant fabricated components for nuclear weapons, employing radioactive materials such as plutonium and uranium, and various nonradioactive materials including beryllium and stainless steel. Components manufactured at the plant were shipped offsite for final assembly. Support activities included chemical recovery and purification of recyclable transuranic radionuclides, and research and development in metallurgy, machining, nondestructive testing, remote engineering, chemistry, and physics. During production, both radioactive and nonradioactive wastes were generated and stored or disposed on site. The preliminary environmental assessment performed under the environmental restoration program identified locations of past onsite storage, and locations of potential environmental contamination (EG&G, 1991).

The site was originally named "Rocky Flats Plant", based on its industrial mission. Recently, the site was renamed "Rocky Flats Environmental Technology Site" (RFETS), based on its transition from a defense production facility to one whose future includes environmental restoration, waste management, and decontamination and decommissioning. The maintenance of a production contingency remains one of the missions of the facility..

1.5 Overview of Groundwater Monitoring Program

Groundwater protection at RFETS has been defined as the prevention, monitoring, and remediation of contaminated groundwater in the vicinity of the site. The overall objective of the Groundwater Monitoring Program is to identify groundwater resources in the vicinity of RFETS and protect those resources from further or potential degradation. The specific objective of the program is to assess the quality and quantity of the groundwater resource to enable proper management of that resource (EG&G, 1993b). Elements of the program include measurement of hazardous constituent concentrations in groundwater, determination of the gradient and direction of groundwater flow, and assessment of the nature and extent of any contaminant plumes in the uppermost aquifer within RFETS boundaries.

Until 1974, wells in the groundwater monitoring network at RFETS were sampled annually. Semi-annual sampling was conducted from 1974 to 1980, then increased to three times per year until 1982. Since 1982, monitoring wells have been sampled on a quarterly basis.

The current Groundwater Monitoring Program is a blend of several separate monitoring programs that address distinct regulatory compliance or site investigation objectives. Most of the wells at RFETS were not installed as part of an integrated sitewide monitoring network but rather to fulfill those site- or investigation-specific data needs. The resulting monitoring well network consists of the following six categories of monitoring wells:

- RCRA Regulatory Wells - Used to characterize and/or monitor the uppermost aquifer for Resource Conservation and Recovery Act (RCRA) units;
- RCRA Characterization Wells - Used to characterize and/or monitor aquifers other than the uppermost aquifer at or near RCRA units;
- CERCLA Wells - Installed to characterize and/or monitor the groundwater of Comprehensive Environmental response, Compensation and Liability Act (CERCLA) units;
- Boundary Wells - Monitor the groundwater in areas downgradient of RFETS, at the site boundary;
- Background Wells - Monitor the groundwater in areas upgradient or cross-gradient of RFETS; and,
- Special Purpose Wells - Other wells installed at RFETS.

1.5.1 Groundwater Monitoring Well Network

As of the second quarter 1994, the operational groundwater monitoring network consists of 355 wells. The 355 wells in the network is less than the total of 655 wells present on site as a result of ongoing evaluations of the monitoring program in terms of sitewide regulatory requirements, plant protection objectives, and characterization objectives. The 1991 *Well Evaluation Report* (EG&G, 1991) identified wells for abandonment under the Well Abandonment and Replacement Program (WARP) using the following criteria: wells installed prior to 1986, incomplete construction details, physical or mechanical damage to the well, groundwater pH greater than 10 (suggesting cement grout contamination), total depth discrepancies in the data, inappropriate casing materials, foreign materials in the well, well location subject to flooding, and missing sealant materials. In addition, inclusion in the network has been judged based on the utility of a well to the objectives of the Groundwater Monitoring Program.

The number of wells included in the groundwater monitoring network varies as wells are abandoned under WARP and as ongoing site investigations change. During the second quarter of 1994, the number of wells sampled, per category were:

- 76 RCRA Regulatory Wells;
- 12 RCRA Characterization Wells;
- 212 CERCLA Wells;
- 7 Boundary Wells;
- 2 Background Wells; and,
- 46 Special Purpose Wells.

Well locations and classifications are shown on Figure 1-2.

The methods and materials used in construction of more than 600 monitoring wells have varied somewhat during the eight-year Groundwater Monitoring Program. Nonviable wells have been removed from the monitoring program as part of WARP. As a result, construction materials used in the wells are not likely to impact water quality. All currently active wells were constructed using industry standard practices and Type-316 stainless steel or Schedule 40 polyvinyl chloride (PVC) casing and screen. A summary of well construction information for wells installed since 1986 is shown in Table 1-1 (EG&G, 1993b).

TABLE 1-1
SUMMARY OF WELL DESIGN FROM 1986-1993

Installation Year	Casing Type	Screen Opening (in.)	Sandpack U.S. Geological Survey (USGS) Sieve Size
1986 Alluvial Wells	2-inch diameter Type-316 SS	0.010, 0.020	16-40, 32-42, 12-20
1986 Bedrock Wells	2-inch diameter Type-316 SS	0.010, 0.020	16-40, 32-42, 12-20
1987 Alluvial Wells	2-inch diameter Type-316 SS	0.010	32-42
1987 Bedrock Wells	2-inch diameter Type-316 SS	0.010	32-42
1989 Alluvial Wells	4-inch diameter Sch 40 PVC*	0.010	32-42
1989 Piezometers	2-inch diameter Sch 40 PVC*	0.010	32-42
1989 Shallow Bedrock Wells	2-inch diameter Sch 40 PVC*	0.010	32-42
1989 Deep Bedrock Wells	2-inch diameter Sch 40 PVC*	0.010	32-42
1990 Landfill Siting Wells	2-inch diameter Sch 40 PVC**	0.010	16-40, 8-12 with Prepack 16-40
1990 French Drain	2-inch diameter Sch 40 PVC***	0.010	16-40
1991 All Wells	2-inch diameter Sch 40 PVC*	0.010	16-40
1992, 1993 All Wells	2-inch diameter Sch 40 PVC*	0.010	16-40

Legend:

SS = Stainless Steel
Sch 40 PVC = Schedule 40 Polyvinyl Chloride
* = 1 or 2 ft. Sump
** = 5 ft. Sump
*** = Varying Sump Lengths

Source:

EG&G, 1993b

1.5.2 Groundwater Monitoring Field Activities

Activities conducted as part of the Groundwater Monitoring Program include quarterly sampling and analysis; weekly, monthly, and quarterly measurement of groundwater elevations; well maintenance; and well abandonment and replacement. All work activities are conducted according to EMD SOPs. The SOPs are intended to provide a means to produce data that are: representative of groundwater quality, comparable from well to well, and reproducible for any given well (EG&G, 1993b).

A summary of the field activities conducted during the Groundwater Monitoring Program is presented in the following sections. Much of the discussion is drawn from the *Groundwater Protection and Monitoring Program Plan* (GPMPP) (EG&G, 1993b).

1.5.2.1 Quarterly Sampling and Analysis

The current (third quarter 1994) operational groundwater monitoring well network consists of 355 wells. Wells containing sufficient water are sampled each quarter. The criteria for judging sufficient water in a well is presented in the SOPs. A sampling schedule is developed at the beginning of each quarter to establish an approximate quarterly time interval (three months) between samples at any given well, and to ensure compliance with the sampling schedules mandated by various regulatory requirements. The schedule is used as a guide (except as required by specific regulations) and may be modified as needed to account for unplanned changes that occur during the sampling quarter.

EMD SOP GW.6 *Groundwater Sampling* (EG&G, 1994d) describes the procedures for the collection of all groundwater samples. Fundamental aspects of the procedures are as follows:

- Sampling techniques should not introduce contamination to samples or wells.
- All downhole equipment should be made of inert materials. Techniques for the use of this equipment should ensure a high-level of sample integrity and minimize the potential for cross contamination of samples or contamination of any well with foreign materials.
- Sampled water should be representative of formation water.

- All sampling devices are to be designed for the collection of samples that reflect actual formation geochemical conditions. Well productivity is an important consideration in employing the sample equipment. Often formations at RFETS produce insufficient water to sustain a constant well water level during purging, and some wells dewater. To minimize potential chemical changes to well water from the effects of overdraught, specific recharge volumes and sampling times have been established.

- All water collected after purging criteria are met are considered to be homogeneous. Replicates collected as split samples for regulatory agencies are assumed to be identical to samples collected for EG&G.

- All sampling techniques are standardized to ensure reproducibility of results.

- All field sample crews are trained in the techniques described in the SOPs; and standardized equipment is used during the sampling events. This approach minimizes sampling variability.

- Whenever there are limited sample volumes available for collection, and samples for the full analyte list cannot be collected, sample analyses are prioritized.

- Identification and collection of immiscible fluids are required by and described in the SOPs.

1.5.2.2 Measurement of Groundwater Elevations

Water level data are collected periodically in RFETS wells and piezometers to provide data needed to monitor changes in potentiometric elevations. The data are used by EG&G to produce potentiometric maps that portray groundwater elevations, directions of flow, and gradients (EG&G, 1994b). Water levels are measured using procedures described in SOP GW.1 *Water Level Measurements in Wells and Piezometers* (EG&G, 1994d).

Various operational and regulatory compliance requirements result in quarterly, monthly, and weekly schedules for collecting water level data. The SOP requires that data be collected over a short time interval at the beginning of a scheduled sampling round in order to obtain time-correlated groundwater elevations. To achieve this, quarterly measurements are collected during the first 10 working days of a quarter, utilizing two to four sampling crews. Monthly measurements are collected during the first five working days of the month, and weekly measurements are collected during the first day of the week. During the second quarter 1994, 523 wells were monitored on a quarterly basis. Of These wells, 151 were also monitored on a monthly basis, and 13 wells were monitored on a weekly basis.

1.5.2.3 Well Maintenance

The physical condition of all wells in the program is monitored on an ongoing basis. Information concerning the integrity of a well is collected during quarterly water level monitoring work. Factors noted in evaluating the integrity of a well include:

- Accumulation of sediment in a well;
- Integrity of concrete well pads;
- Condition of elevation reference points; and,
- Condition of surface completion (e.g., secure locking cap, plumb protective cover, debris inside protective cover, encroaching vegetation).

The most common maintenance activities performed include: redevelopment of wells with excessive accumulation of sediment, replacement of concrete well pads, repair or replacement of locking caps, addition of insect deterrents, and control of vegetation. Typically 10 to 15 wells require maintenance each quarter.

1.5.2.4 Well Abandonment and Replacement

Wells are considered for abandonment, or in some cases, replacement, when the utility of the well is exceeded by its liability with respect to the quality of data collected. Wells are evaluated and identified for abandonment or replacement as part of the WARP.

1.5.3 Analytical Suites

The current Groundwater Monitoring Program provides samples for a number of analytical suites. Suites are designed to meet the needs of the various RCRA Operable Units (OUs), the existing landfill, specific suites to support three site investigations, and other relevant federal and state requirements. As of the third quarter 1994, samples for 15 different analytical suites were collected, labeled, screened for radiation, and shipped to analytical laboratories.

1.5.4 Field Staffing

As of the third quarter 1994, a staff of 14 personnel were assigned to complete the required field activities of RFETS Groundwater Monitoring Program. Field office personnel include the Site Manager, Health and Safety Specialist, Database Manager, Sample Manager, and Field Office Assistant. A field sampling staff consisting of four two-person sampling crews (and an alternate crew) implement water level monitoring, purging and sampling, initiating chain of custody, monitoring well installation, redeveloping wells, and other special tasks such as well hydraulic testing and post-sampling water level recovery monitoring.

2.0 SITE CONDITIONS

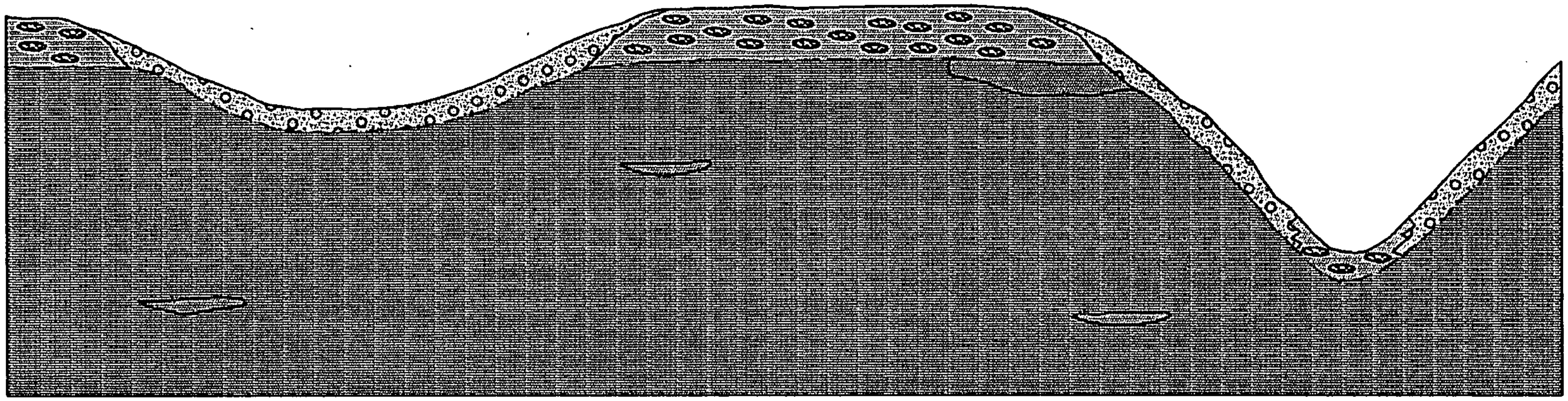
Geologic and hydrogeologic conditions are briefly described in the following sections in order to characterize the site groundwater conditions as they relate to the operational aspects of the Groundwater Monitoring Program. Natural conditions influence the design depths of wells, screened intervals selected, and productivity and recovery rates of wells in the groundwater monitoring network. Well performance characteristics influenced by aquifer conditions play a primary role in the types of purging, sampling, and field parameter measurement methods that can be successfully used at RFETS.

2.1 Geology

RFETS is located on the Colorado High Plains approximately two to six miles east of the Front Range mountain front. The geologic materials at RFETS can be grouped into two general categories: unconsolidated surficial deposits and underlying consolidated bedrock (EG&G, 1994b). Figure 2-1 is a generalized geologic cross section that illustrates the surficial and bedrock materials within each group.

East of a Precambrian-age mountain core, the gently eastward-dipping Cretaceous-age bedrock was subjected to erosion. This produced a broad, flat erosional surface (a peneplain). The bedrock surface was overlain by the heterogeneous sediments of the Rocky Flats Alluvium at the end of the Pleistocene Epoch (EG&G, 1994b). Beginning in the Holocene, headward erosion by westward progressing drainages incised both the Rocky Flats Alluvium and the underlying bedrock peneplain. Approximately half of the surface area covered by RFETS has been incised, removing the Rocky Flats Alluvium. In some areas, these Holocene and younger erosional surfaces have been subsequently covered by stream sediments or colluvium (Figure 2-2).

A summary of the stratigraphic profile is presented in the following sections. Younger units are described first, followed by progressively older, deeper units.



EXPLANATION

AGE

QUATERNARY — UNCONSOLIDATED SURFICIAL DEPOSITS

VALLEY FILL: clay, silt, and pebbly sand with silty and cobbly gravel lenses.

COLLUVIUM: clayey coarse gravel and coarse sand, slope debris derived from Rocky Flats Alluvium and outcropping bedrock.

ROCKY FLATS ALLUVIUM: poorly sorted, angular to subrounded cobbles, coarse gravels, coarse sands, and gravelly clays, lenses of clay, silt, and sand.

CRETACEOUS — CONSOLIDATED BEDROCK

BEDROCK: claystone and siltstone, varying amount of clay, silt, and sand, weathered intervals, sandstone lenses.

- - - - - - - - EROSIONAL UNCONFORMITY

Modified from EG&G, 1994b.

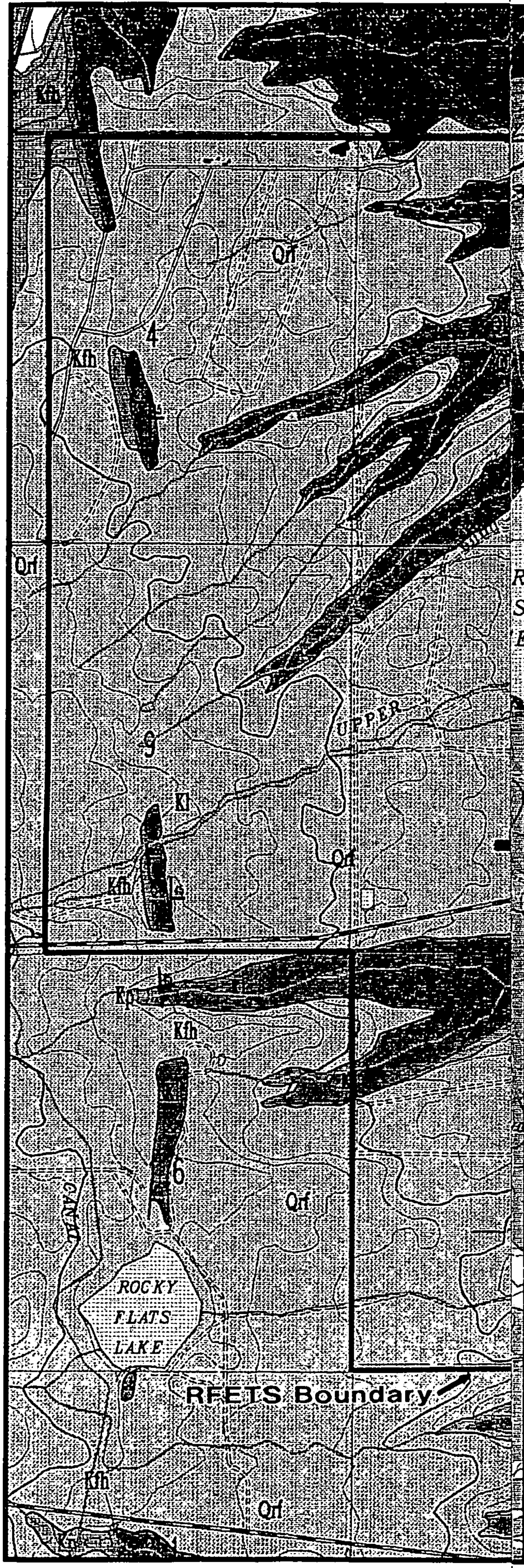
EG&G ROCKY FLATS

Rocky Flats Environmental Technology Site, Golden Colorado

GENERALIZED GEOLOGIC CROSS SECTION AND LITHOLOGIC DESCRIPTIONS

WELL EVALUATION REPORT

DATE : MARCH 1995	FIGURE : 2-1



EXPLANATION

- Af Artificial Fill
- Qa Valley Fill Alluvium (Holocene)
- Qls Landslide Slump (Holocene)
- Qta Undifferentiated Alluvium (Pleistocene)
- Qrf Rocky Flats Alluvium (Pleistocene)
- Ka Arapahoe Formation (Cretaceous)
- Kl Laramie Formation (Cretaceous)
- Kfh Fox Hills Sandstone (Cretaceous)
- Kp Pierre Shale (Cretaceous)

Strike and dip of bedding planes in bedrock

50 inclined | vertical | 20 overturned | horizontal

Gravel, sand, or clay pit

BM Benchmark

Area of bedrock exposure

Contact
dashed where approximately located;
dotted where concealed

From: EG&G, 1993d, "Groundwater Geochemistry of Rocky Flats Plant"

SCALE 1" = 2000'

2000' 0 2000'

EG&G ROCKY FLATS

Rocky Flats Environmental Technology Site

Geologic Map

Of

Rocky Flats Environmental Technology Site

1994 Well Evaluation Report

Date: March 1995	Figure 2-2

2.1.1 Unconsolidated Deposits

The surface of RFETS is covered by a layer of unconsolidated Quaternary deposits that consist of Holocene colluvium and Valley-fill Alluvium, and Pleistocene Rocky Flats Alluvium. Holocene slump and landslide material is also present locally.

Colluvial deposits, which are present on the valley slopes in the central portion of RFETS, were derived from geologic material exposed on the steep slopes and topographic highs, and were formed by slope wash and downward creep. The colluvium ranges in thickness from 0 to 20 feet, with the thickest sequences occurring at the base of the valley slopes. The colluvium is composed of clay, clayey gravels, and lesser amounts of sand and silt. Slump and landslide deposits were derived from the colluvium and Rocky Flats Alluvium, and are most common on valley slopes along the Rock Creek and Walnut Creek drainages in the northern portion of RFETS. Valley-fill deposits were fluvially derived from upstream materials, and consist of clay, silt, and sand with lenses of gravel. These deposits occur along the drainage bottoms in and adjacent to stream beds, and are most common in the eastern portions of RFETS. Thicknesses range from 0 to 25 feet (EG&G, 1994b).

Pleistocene deposits consist primarily of the Rocky Flats Alluvium, which is the most prevalent unconsolidated surficial deposit at RFETS. The Rocky Flats Alluvium ranges in thickness from 0 to 100 feet and forms a broad layer that extends across most of the western portion of RFETS (EG&G, 1994b).

Lithologic logs developed from boreholes drilled at RFETS indicate that the unconsolidated material consists of poorly-sorted coarse gravels, coarse sands, and gravelly clays with discontinuous lenses of clay, silt, and sand. The borehole logs also reveal the relatively high degree of heterogeneity in the Rocky Flats Alluvium (EG&G, 1994b).

2.1.2 Consolidated Bedrock Deposits

The unconsolidated surficial deposits unconformably overlie the claystone, siltstone, and sandstone bedrock of the Upper Cretaceous Arapahoe and Laramie Formations. The Arapahoe is predominantly claystone and siltstone, and at RFETS has been shown to contain a mappable but discontinuous basal sandstone unit. That unit has been designated the Number 1 Sandstone (EG&G, 1994b). The configuration of the Arapahoe Formation underlying RFETS is subject to controversy. The formation is described in an investigation as approximately 150 feet thick beneath the central portion of RFETS (EG&G, 1994c), while in a more recent investigation the formation is described as less than 50 feet thick at that location (EG&G, 1994b). Regardless of the thickness of the Arapahoe Formation at RFETS, the No. 1 Sandstone is the uppermost sandstone of significant lateral extent, and is of concern as a potential contaminant transport pathway.

The No. 1 Sandstone is a fine- to medium-grained locally conglomeratic, moderately- to poorly-sorted sandstone interpreted as deposited in a fluvial environment (EG&G, 1994c). The No. 1 Sandstone is isolated by substantial thicknesses of low permeability claystone. Given the isolated and elongated geometry of the No. 1 Sandstone, this dominant groundwater flow pathway is vertically and laterally limited. The No. 1 Sandstone is, however, in hydraulic connection with the overlying unconsolidated surficial deposits in some areas at RFETS, specifically where the sandstone is in close contact with the unconsolidated deposits.

The Laramie Formation unconformably underlies the Arapahoe Formation and is approximately 600 to 800 feet thick. The Laramie Formation is subdivided into two members. The upper member of the Laramie Formation is 300 to 500 feet thick and consists primarily of claystone. The lower member is about 300 feet thick and is composed of sandstones, claystones and coal beds. The upper member is generally much finer-grained than the lower member, but contains several separate and discontinuous sandstone units designated the No. 2 through No. 5 Sandstones. These sandstone units are probably not significant from a sitewide groundwater monitoring perspective because they are encased in claystones, are not in hydraulic connection with the No. 1 Sandstone, and occur at greater depths. These lenticular Laramie Formation sandstones are texturally distinct from the No. 1 Sandstone by virtue of their high silt and clay content (EG&G, 1994c).

The Upper Cretaceous Fox Hills Sandstone conformably underlies the Laramie Formation and ranges from 90 to 140 feet in thickness. In general, the Fox Hills Sandstone is a very fine- to medium-grained, angular to subrounded, well-sorted silty sandstone. The Fox Hills Sandstone is an aquifer of regional significance, which lies at a depth of 700 to 800 feet below ground surface at RFETS. Underlying the Fox Hills Sandstone are several thousand feet of the Lower Cretaceous Pierre Shale and older units.

Lithologic logs from boreholes drilled in the shallow bedrock material indicate a predominance of claystones and siltstones with lesser amounts of sandstone (EG&G, 1994b). In general, the bedrock exhibits a higher percentage of fine-grained material, with relatively low permeability and volume of groundwater flow compared to the overlying unconsolidated surficial deposits. Also evident from the borehole logs is a weathered zone in the upper portion of the bedrock. Fracturing and weathering increase the permeability of bedrock material. The weathered zone is commonly less than 15 feet thick, but may be as thick as 60 feet. The thickness of the weathered bedrock zone is dependent on factors such as relative abundance of fractures, presence of root zones, elevation relative to the water table, and proximity to valley bottoms.

2.1.3 Structural Features

The bedrock strata exposed immediately west of RFETS have been folded into steeply eastward-dipping exposures of the Fox Hills Sandstone and Laramie Formations. These units receive recharge from precipitation along the exposed hogbacks northwest and southwest of RFETS. The formations also receive recharge from the overlying Rocky Flats Alluvium and Arapahoe Formation.

Small-scale structural features such as joints and fractures are present in the bedrock units. Joint and fracture surfaces are commonly coated with secondary oxide and hydroxide minerals in the weathered portion of the bedrock units. Slickensides are also present on some fracture surfaces.

The presence of such features increases secondary porosity and permeability and may facilitate groundwater transport through bedrock units by providing preferential flow paths in otherwise low permeability claystones.

2.2 Hydrogeology

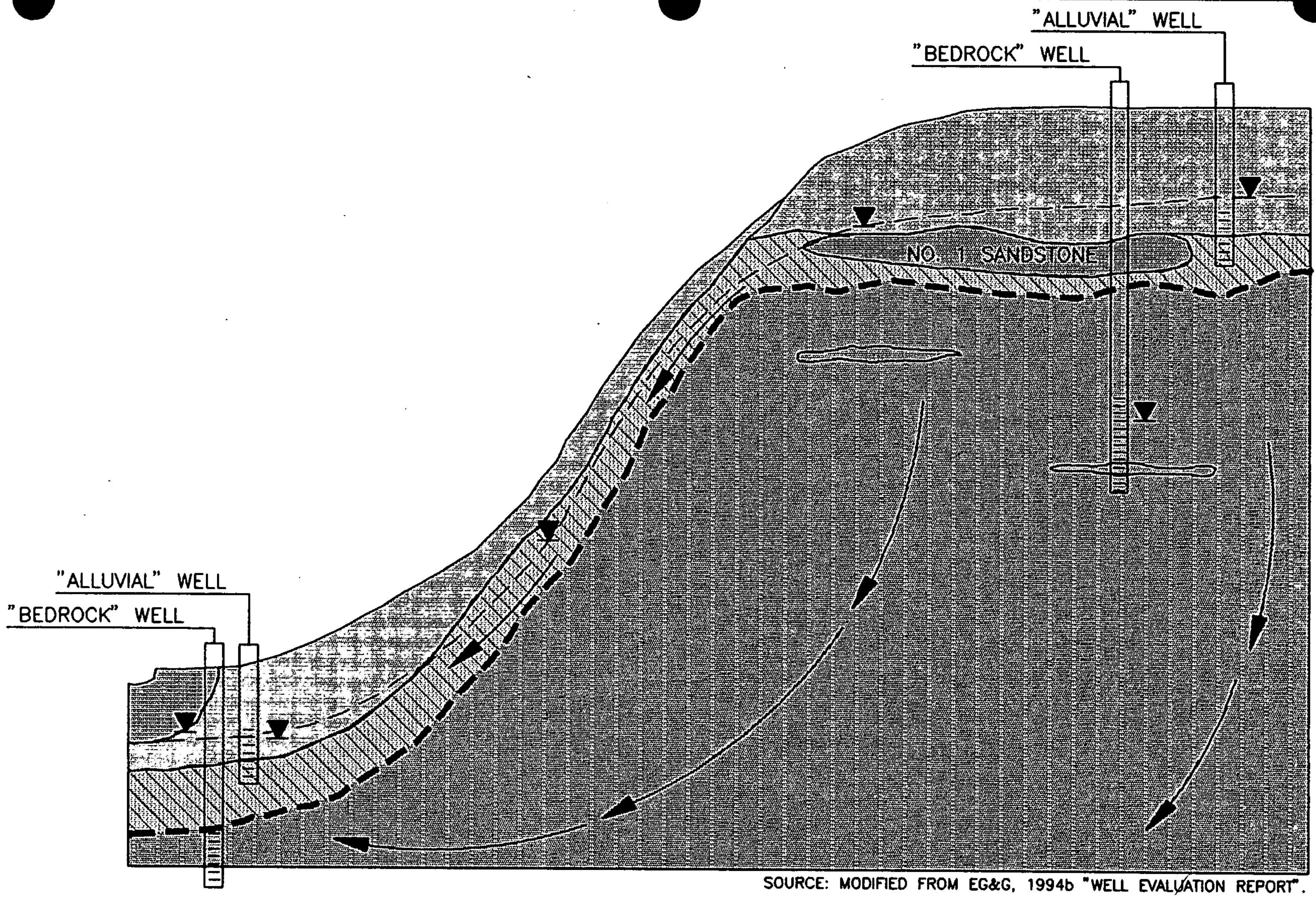
2.2.1 Hydrostratigraphy

Describing geologic materials in terms of hydrostratigraphic units is useful in discussions of hydrogeology because the relative hydrologic properties of materials are considered rather than the lithologic properties. It is the contrast in hydrologic properties that determines the characteristics of groundwater flow. At RFETS, groundwater flows in two hydrostratigraphic units. The upper hydrostratigraphic unit consists of the distinct lithologic units of the Rocky Flats Alluvium, colluvium, valley-fill Alluvium, landslide deposits, weathered Arapahoe and Laramie Formation bedrock, and any sandstone units within the Arapahoe and Laramie Formations that are in hydraulic connection with the overlying unconsolidated surficial deposits or with the ground surface. The lower hydrostratigraphic unit is composed of the unweathered bedrock of the Arapahoe and Laramie Formations, excluding the sandstone units included in the upper hydrostratigraphic unit. The upper and lower hydrostratigraphic units are depicted on Figure 2-3.

Monitoring wells at RFETS are described as being installed into either the "Alluvium" or the "Bedrock". Those terms are used in the Groundwater Monitoring Program to indicate completion into either the upper or lower hydrostratigraphic units. The monitoring network consists of approximately 65 percent alluvial wells, 30 percent bedrock wells, and 5 percent combined alluvial and bedrock wells.

2.2.2 Groundwater Flow Conditions

A conceptual model has been proposed (EG&G, 1993b) that represents the overall groundwater flow system at RFETS. The model identifies three general zones with distinct groundwater flow



SOURCE: MODIFIED FROM EG&G, 1994b "WELL EVALUATION REPORT".

UPPER HYDROSTRATIGRAPHIC UNIT
- ROCKY FLATS ALLUVIUM
- SANDSTONE
- WEATHERED CLAYSTONE BEDROCK
- COLLUVIUM
- VALLEY FILL ALLUVIUM

LOWER HYDROSTRATIGRAPHIC UNIT
- UNWEATHERED CLAYSTONE BEDROCK

- WATER TABLE
- POTENTIOMETRIC LEVEL
- GENERAL DIRECTION OF GROUNDWATER FLOW
- BOUNDARY BETWEEN UPPER AND LOWER HYDROSTRATIGRAPHIC UNITS

EG&G ROCKY FLATS

Rocky Flats Environmental Technology Site, Golden Colorado

CONCEPTUAL HYDROGEOLOGIC MODEL

DATE : MARCH 1995	FIGURE : 2-3

2715A011.DWG

characteristics. These zones can be described as north-south bands that occupy the western, central, and eastern portions of the plant site.

The western zone is characterized by a relatively unbroken gentle topographic slope formed on the Rocky Flats Alluvium. In this zone, alluvial thicknesses are greatest, water level fluctuations are minor, and the alluvium is rarely, if ever, completely unsaturated. Groundwater in the upper hydrostratigraphic unit flows generally east with slight variations according to the configuration of the bedrock surface. The predominantly claystone bedrock impedes downward vertical migration of groundwater and directs flow laterally in the unconsolidated surficial materials.

The central zone is an extension of the western zone but differs in that it is incised by east-west-trending drainages. These erosional features yield the most significant topographic variation at RFETS. Topographic highs are capped by thick alluvial deposits and flanked by colluvium. Water flowing through the capping alluvium follows the bedrock surface and either emerges as seeps, drains into the hillside colluvium, or migrates vertically into lower lithostratigraphic bedrock units. The potentiometric surface of the groundwater in the upper hydrostratigraphic unit generally mimics both the ground and the top of bedrock surfaces. The potentiometric surface slopes gently to the east and more steeply northward and southward down the hillslopes of the drainage valleys. Groundwater flows from broad areas of recharge (located upgradient and on nearby topographic highs) toward the erosional limit of alluvium, and then directly toward creeks in the drainage bottoms. Groundwater and surface water are locally in direct connection at seeps and in alluvial deposits along these drainages. In areas of relatively steep topography, baseflow to creeks may occur. The paleotopographic surface also plays a role in directing groundwater flow and, where locally high, in the development of unsaturated zones in unconsolidated surficial deposits. Channels and depressions in the top-of-bedrock surface may act as conduits or small collection basins for groundwater. Surficial deposits on either side of these channels can be dewatered by flow toward the channels.

The eastern zone is characterized by relatively flat surface topography, the absence of Rocky Flats Alluvium, and more widespread Valley-fill alluvial deposits. The ground surface is generally covered by thin deposits of colluvium. The hydraulic gradients are relatively low, and groundwater in unconsolidated surficial deposits generally flows eastward and only locally toward the axes of stream valleys. Baseflow to creeks is probably also diminished relative to the central zone as a result of the lower hydraulic gradients.

2.2.3 Hydraulic Conductivities

In general, the upper hydrostratigraphic unit at RFETS has a low to moderate hydraulic conductivity and typically yields small amounts of water to monitoring wells. Hydraulic testing of the wells indicates that the upper hydrostratigraphic unit exhibits a wide range of hydraulic conductivities because of the diverse nature of the individual geologic materials that comprise the unit. Values of hydraulic conductivity range from as high as 3×10^{-2} centimeters per second (cm/sec) in localized areas of the Valley-fill Alluvium in the stream drainages, to as low as 9×10^{-7} cm/sec in the clay lenses of the Rocky Flats Alluvium (EG&G, 1993b). Hydraulic conductivities in the weathered bedrock portion of the upper hydrostratigraphic unit range from 10^{-5} to 10^{-6} cm/sec. As has been described, the weathered bedrock is made up of both the weathered claystone and the No. 1 Sandstone unit. Average values, calculated as geometric means, are 10^{-4} cm/sec for the colluvium and Rocky Flats Alluvium, and 10^{-3} to 10^{-4} cm/sec for the Valley-fill Alluvium in Woman Creek and Walnut Creek, respectively (EG&G, 1994c).

Hydraulic conductivities in the lower hydrostratigraphic unit are significantly lower than those of the overlying unit, with values ranging from 10^{-6} to 10^{-8} cm/sec in the unweathered claystone bedrock.

The contrast in hydraulic conductivities between the upper and lower hydrostratigraphic units creates a zone of saturation at the base of the upper hydrostratigraphic unit. Because of low bedrock permeability, vertical flow rates are substantially lower than horizontal flow rates and relatively minor amounts of groundwater enter the unweathered claystone bedrock (EG&G, 1994c).

2.2.4 Groundwater Interaction Between Hydrostratigraphic Units

Groundwater in the upper hydrostratigraphic unit is unconfined, while in the lower hydrostratigraphic, groundwater is known to occur as both confined and unconfined. Groundwater in the scattered sandstone units of the Arapahoe and Laramie Formations is typically confined, although unconfined conditions occur where the Arapahoe Formation sandstone units subcrop beneath the alluvial material. At these subcrops, groundwater in the upper hydrostratigraphic unit is in hydraulic connection with groundwater in the lower hydrostratigraphic unit, resulting in unconfined groundwater in the sandstone units. The Arapahoe No. 1 Sandstone subcrops in the eastern portion of the Industrial Area and to the east at the end of the topographic high, at which point it is considered part of the upper hydrostratigraphic unit. Subcrops of the lower sandstone of the Laramie Formation (Sandstone Nos. 2, 3, 4, and 5) also occur along the slopes of the drainages. However, the extent of the area of subcrop contact is small due to the limited size of the units. The confining layers for the sandstones are the claystones and silty claystones of the Laramie Formation (EG&G, 1993b).

3.0 FIELD EVALUATION

The purpose of the field evaluation was to provide a means to assess and compare technologies and field methodologies identified as viable alternatives to certain current Groundwater Monitoring Program procedures. As discussed in Section 1.1, one of the field tasks for this Well Evaluation Report was to evaluate existing Groundwater Monitoring Program methodologies for measuring field parameters with the objective of improving the quality and validity of the data. Another task was to evaluate alternative well purging and sample collection methods with the objective of minimizing sediment and turbidity in groundwater samples.

A field program was designed to collect data that allowed a direct comparison between alternative equipment and methods, and between those alternatives and current Groundwater Monitoring Program procedures. Data and information collected included:

- Qualitative factors related to the ease of calibration and use, general ruggedness, and ease of maintenance of field parameter instrumentation and pumping systems; and,
- Quantitative factors related to the performance of equipment, including: automated data acquisition of field water quality parameters, manual recording of water quality parameters to supplement and verify the automated data, flow rate data from pumping systems during purging and sampling, automated water level drawdown data to enable control over pumping rates, and the collection of groundwater samples for laboratory analysis.

Conducting the field evaluation first required development of an experimental approach to be used in the field. The following aspects of the field evaluation were considered:

- Design of a specific field evaluation methodology;
- Selection of wells to be used in the field program;
- Selection of alternative field parameter measurement instrumentation; and,
- Selection of alternative purging and sampling pump systems.

A discussion of each of these aspects is presented in the following sections.

3.1 Design of the Field Evaluation Methodology

The field evaluation required an objective comparison of equipment and methodologies under controlled field conditions. Specific considerations used in the design of the field program are listed below.

- Develop a method that allows direct comparison of equipment and methods. This would entail sampling a limited number of wells using each of the field parameter instrumentation and pumping systems which were to be evaluated.
- Select wells that generally represent the range of expected recovery rates and lithologies in wells at RFETS.
- Use identical methods for all purging and sampling events.
- Develop field forms to ensure consistent collection of data for all purging and sampling events. The forms augment the field forms required by the SOPs.
- Perform tests only after pumps have been installed for a minimum of 24 hours. This requirement minimizes the impacts from the turbulence resulting from removal of a pump from a completed test and insertion of a pump for the next test.
- Perform bailed events after pumped events were completed at each well, to minimize impacts from turbidity on subsequent tests.
- Gain experience with the equipment prior to the field evaluation by conducting dry runs and by hands-on demonstrations by representatives of the equipment manufacturers and distributors.
- Collect samples for analytical testing at the completion of each of the purge events. Filtered and unfiltered samples were collected according to the procedures outlined in RFETS SOPs. Analysis for metals, volatile organic compounds (VOCs), and radionuclides were conducted. The results of analyses were used to compare the performance of both the field parameter instrumentation and pumping systems.

3.2 Selection of Wells Used in the Field Evaluation

Well selection was considered critical for maintaining control over the variables being evaluated. The selection process considered the need for wells to be both representative of the broad range in well performance and conditions at RFETS, and to maintain a narrow range of test conditions so as not to mask the test data. In addition, certain elements which would aid in evaluating the systems needed to be present. For example, detectable contamination and significant turbidity in the well water helps evaluate the ability of a pump to produce representative samples under these conditions.

Four wells were selected for the field evaluation; each well was sampled once by each of four different pumps. All four wells were also sampled by the current bailing method to compare performance of the alternative pumps to the traditional RFETS sampling methods. The following criteria were considered in selecting the wells:

- Both bedrock and alluvial wells were evaluated, to assess any significant differences between geologic materials related to sample water quality, turbidity, and well production.
- All wells had to have a history of detectable radionuclide and/or volatile organic compound contamination and significant turbidity, since the viability of future use of the pump systems at RFETS depended on whether the systems produced representative groundwater samples from wells exhibiting these characteristics.
- All wells had to be representative of typical RFETS well construction methods and have a two-inch diameter screened interval.
- The static water levels in the wells had to be located within the screened zone. This criterion was important because the numerous pump insertions and removals during the evaluation would mix screened-zone water with stagnant water above the screened zone. By using wells which had no stagnant zone above the well screen, mixing was not a concern.
- Historic static water levels had to be relatively stable. Large water level fluctuations implied fluctuations in water chemistry which may have the potential to interfere with analytical results of samples collected over the two-week duration of the field evaluation. This was a difficult criterion to meet since most RFETS wells display moderate to large (10 to 20 feet) seasonal water level fluctuations.

- There had to be sufficient standing water in the well to allow submergence of a pressure transducer below the full submergence of the typical three-foot pump length. Five feet of standing water was considered the minimum for the evaluation.

- The recovery rates of the wells had to represent the general range in well production capacities of the monitoring wells at RFETS. Slow and rapid recovery wells needed to be part of the evaluation.

A review of RFETS monitoring wells in light of the criteria listed above identified nine candidate wells. Of the nine wells, four were selected for testing. The other five wells served as alternates in the event that any of the selected wells proved unsatisfactory during the field evaluation. Substitution of one selected well occurred during initial field work when it was determined that Well 0487 had too low a recovery rate to maintain the test schedule. Well 0487 dewatered after two liters were pumped at a rate of less than 35 ml/min. Well 20591, which displayed a slightly greater pumping rate capability (approximately 65 ml/min) replaced Well 0487, allowing maintenance of the test schedule.

The four wells ultimately selected (1786, 2587, 20591, and 41691) displayed the following general characteristics:

- Lithology in screened interval: Two wells in the Valley-fill Alluvium (1786 and 41691), one in the Rocky Flats Alluvium (20591), and one in the bedrock (2587);

- Recovery Rates: Three are considered "1-day" wells and one (20591) is considered a "2-day" well, based on quarterly sampling records in the Groundwater Monitoring Program.

- Presence of detectable contamination: Wells 1786 and 2587 have historic detectable concentrations of both VOCs and radionuclides, and Well 41691 has historic detections of radionuclides but no VOC detections. Well 20591 has no historic analytical data, although owing to its location immediately down gradient of the Mound and the 903 Pad, the well was suspected to have detectable concentrations of both VOCs and radionuclides. In addition, Well 20591 is located immediately adjacent to Well 1787 (abandoned) which contained detectable contamination. None of the wells are located in Radiologically Controlled Areas (RCAs) or Individual Hazardous Substance Sites (IHSSs), and none have historic high contaminant concentrations. These latter issues minimized health and safety concerns for personnel conducting the field evaluation, and minimized access concerns associated with RCAs and IHSSs.

- Water Levels: The most recent data indicate that all wells have water levels within the screened intervals. Based on hydrographs (EG&G, 1994b), all wells display relatively low to moderate seasonal water level fluctuations. In addition, all wells contained sufficient standing water columns to allow submergence of both the pumps and downhole transducers.

Figure 3-1 shows the location of the four wells used in the evaluation. A summary of the wells relative to the selection criteria is presented on Table 3-1. Table 3-2 presents well construction details, lithology of the screened interval, and hydraulic conductivity values (if available).

3.3 Selection of Field Parameter Instrumentation

State of the art field parameter instruments were selected for inclusion in the field evaluation. Suitability criteria were established to achieve the 1994 WER objectives of evaluating methods to improve field parameter measurements. The criteria used to evaluate the instruments focused on instrument capabilities, advanced instrument technology, and ability of the instruments to utilize flow cells. Evaluation of flow cell measurement methods was viewed as critical in light of recent research which has identified that the water chemistry of samples is often affected by turbulence and air contact during the transfer of the sample from a bailer or pump to a beaker for parameter measurement (EPA, 1994b; FERMC, 1993).

A number of instrument manufacturers and users were contacted to identify instruments capable of providing the data required by the Groundwater Monitoring Program. Following a review of the information received from manufacturers and users, the instruments listed below (in alphabetical order) were selected for the field evaluation.

- GeoTech/Orion
- Horiba U-10
- Hydrolab H20
- QED Purge Saver
- Solomat 803PS

TABLE 3-1
WELL SELECTION CRITERIA

Well ID	Location	RCA or IHSS	Formation	Water Level Variation (ft bgs*)	Standing Water Column (ft)	Recovery Rate***	Turbidity (FTUs)	Presence of Contamination Noted Historical Analytical Results			Casing Diameter (in)	Water Level In Screened Interval
								VOC	Radionuclides	High		
Required Conditions												
N/A	Range	No	Range	Minimal	>5.0	Range	>50	Yes	Yes	No	2.0	Yes
Conditions in Candidate Wells												
0786	Landfill	No	Recent Alluvium	4.7-5.3	2.71	2-Day	31	No	Yes	No	2.0	Yes
1086	Landfill	No	Rocky Flats Alluvium	2.4-16.9	14.23	2-Day	196	Yes	Yes	No	2.0	Yes
1786	Solar Ponds	No	Recent Alluvium	4.5-16.5	9.43	1-Day	>300	Yes	Yes	No	2.0	Yes
0487	881 Hillside	No	Colluvium	5.8-15	4.62	2-Day	>300	Yes	Yes	No	2.0	Yes
1887	Mound	No	Bedrock	30.3-32.7	4.72	2-Day	65	Yes	Yes	No	2.0	Yes
2587	East Trenches	No	Bedrock	13.6-29.1	18.4	1-Day	35	Yes	Yes	No	2.0	Yes
20591	East of Plant	No	Rocky Flats Alluvium	Avg. 17.7	7.57	2-Day (suspected)	>300	No Data**	No Data**	No Data**	2.0	Yes
20691	East of Plant	No	Rocky Flats Alluvium	Avg. 17.1	5.91	2-Day (suspected)	>300	No Data**	No Data**	No Data**	2.0	Yes
41691	Indiana Street	No	Recent Alluvium	6.5-10.1	9.96	1-Day	>300	No	Yes	No	2.0	Yes

NOTE:

* bgs = Below Ground Surface
** No historic analytical data for well, but because of location of well, detectable contaminant concentrations are suspected.
*** Recovery rate information from groundwater monitoring program records that indicate whether well is typically purged and sampled on same day, or purged one day and sampled the next. No historic analytical data exists for wells 20591 and 20691.

TABLE 3-2
WELL COMPLETION INFORMATION FOR CANDIDATE WELLS IN THE FIELD EVALUATION

Well No	Location		Borehole Diameter (inches)	Casing Diameter (inches)	Total Well depth (feet bgs)	Depth to top of screen (feet bgs)	Depth to bottom of screen (feet bgs)	Lithology of screened interval		Hydraulic conductivity of screened interval		
	Northing	Easting						completion	unit tested	cm/s	feet/min	method
0786	752827	2083977	7.25	2	5.7	3.0	5.7	Alluvium	Qc	n/d	n/d	n/d
1086	752169	2082491	5.63	2	23.8	3.3	23.8	Alluvium	Qrf	1.4E-06	2.8E-06	Theis
1786	751740	2085242	7.25	2	14.0	3.7	14.0	Alluvium	Qc	4.8E-06 6.5E-06 7.0E-06 2.1E-06	9.4E-06 1.3E-05 1.4E-05 4.1E-06	Bouwer/Rice Hvorslev Cooper et al. Ferris/Knowles
0487	747943	2084887	7.50	2	19.5	3.5	19.5	Alluvium	Qc	6.6E-05 8.0E-05 6.6E-05 6.7E-06	1.3E-04 1.6E-04 1.3E-04 1.3E-05	Jacob Theis Theis Theis
1887	749404	2086339	4.00	2	133.7	127.0	133.5	Bedrock	Kss & Ksslt	1.7E-07	3.3E-07	Hvorslev
2587	749719	2086748	7.50	2	43.7	17.5	43.5	Bedrock	Ksltss & Kss	1.5E-03 7.3E-06 2.3E-03	3.0E-03 1.4E-05 4.5E-03	Bouwer/Rice Bouwer/Rice Bouwer/Rice
20591	749405	2086316	7.25	2	24.6	4.1	24.1	Alluvium	Qrf	2.9E-04	5.7E-04	Bouwer/Rice
20691	749411	2086317	10.00	2	25.0	4.5	24.5	Alluvium	Qrf	3.9E-04	7.7E-04	Hvorslev
41691	753470	2093851	7.25	2	17.1	5.1	14.7	Alluvium	Qa	n/d	n/d	n/d

Qc Quaternary colluvium
Qrf Quaternary Rocky Flats Alluvium
Qa Valley Fill Alluvium
Ksltss & Kss Cretaceous silty sandstone and Cretaceous sandstone
Kss & Ksslt Cretaceous sandstone and Cretaceous siltstone
n/d No data available

In addition to these instruments, a Hach 2100P portable turbidimeter was included in the field evaluation. The Hach instrument was included because it complies with EPA turbidimeter design criteria. The selected instruments listed above that include turbidity sensors utilize LED light source technology rather than the EPA-approved tungsten light source technology (see Section 4.1.1.1).

The ultimate selection of instruments was based on a combination of the suitability criteria identified in Section 4.3, and on the requirements of GW.05 *Field Measurement of Groundwater Field Parameters* (EG&G, 1994d). Instruments needed to: be easy to use, calibrate, and maintain; be adaptable to flow cells; have multiparameter capability; be battery powered and able to operate for a full day without recharging; include some datalogging capabilities; operate within ambient temperatures expected at RFETS; be durable; and measure parameters according to regulatory agency requirements. Additionally, the instruments were to be capable of measuring field parameters within the accuracy range required by EG&G SOPs. The instruments selected were those that most completely met the criteria. Capabilities of the selected instruments are presented in Table 3-3. Features are summarized in Table 3-4 and instrument specifications are summarized in Table 3-5.

3.4 Selection of Purging and Sampling Pump Systems

As described in Section 5.5.1, recent groundwater research has identified low flow rate purging and sampling techniques in concert with dedicated pumping systems as the most suitable method for minimizing sample turbidity. An assessment of available dedicated pump systems capable of pumping at low flow rates was made through contact with pump manufacturers and users. The suitability of a pump was judged by several criteria. The pump must:

- Be capable of dedicated installation and suitable for long-term use with a minimum of maintenance problems;
- Be capable of delivering samples at flow rates of less than 200 ml/min; and,
- Minimize impacts to the water chemistry of a sample.

TABLE 3-3
FIELD PARAMETER INSTRUMENT CAPABILITIES

Instrument	Parameter						Additional Parameters
	pH	Temperature	Specific Conductance	Turbidity	Redox Potential	Dissolved Oxygen	
Current Instruments							
Hach One	X	X					
Hach DR2000				X	X	X	Multiple parameters by AccuVac or titration using ISE
Hach 44600		X	X				TDS
Alternative Instruments Evaluated							
GeoTech/Orion	X	X	X		X	X	TDS, ISE
Hach 2100P				X			
Horiba U-10	X	X	X	X		X	Salinity
Hydrolab H20	X	X	X	X	X	X	TDS
QED Purge Saver	X	X	X		X	X	
Solomat 803PS	X	X	X	X	X*	X	TDS, TSS, Salinity, Ammonia/Ammonium, ISE

<u>NOTES</u>:

ISE = Ion-Selective Electrodes
TDS = Total Dissolved Solids
TSS = Total Suspended Solids
* The Solomat unit used in the field evaluation did not have the optional Redox potential sensor installed.

TABLE 3-4
FIELD PARAMETERS INSTRUMENT FEATURES

Instrument	Feature							
	Type	Dimensions (in)	Weight (lb)	Power Requirements	Battery Life	Ambient Temperature Operating Range (°C)	Flow Cell	Cable Length (ft)
Current Instruments								
Hach One	pH, temperature, mV meter	9x3.5x2.5	4	6v "J" battery	NS	0 to 50	NA	NS
Hach DR2000	Spectrophotometer	8.75x9.5x4.38	4.4	AC or rechargeable battery	1000 measurements	0 to 40	NA	NA
Hach Model 44600	Conductivity, TDS, temperature meter	10.0x7.5x4	2.25	4 "AA" batteries	100 hrs	0 to 50	NA	3 or 10
Alternative Instruments Evaluated								
GeoTech/Orion	GeoTech Flow Cell with Orion: -250A pH meter -124 conductivity meter -820 DO meter	14x8(D) 3.25x7.6x1.9 NS NS	3 NS NS NS	NA 9v battery 9v battery 9v battery	NA NS NS 200 hrs	 5 to 45 NA 0 to 50	240 ml NA NA NA	NA NS NS NS
Horiba U-10	Multimeter	Display: 9.8x3.6x1.8 Sonde: 8.9x3.3(D)	 0.9 1.8	Rechargeable battery	NS	0 to 40	NA	6 or 30
Hydrolab Surveyor 3 H20	Multimeter	Display: 9.5x7.5x5.1 Sonde: 18.2x3.5(D)	 4.2 7.4	Rechargeable battery	Continuous use: 11 hrs 24 hrs	-5 to 50	270 ml	any length up to 300
QED Purge Saver	Multimeter/Flow Cell	18x14x8	13	AC, external battery pack (8 "D" batteries), or internal rechargeable battery	external: 200 hrs internal: 8 hrs	0 to 40	240 ml	NS
Solomat WP4007 803PS	Multimeter	Display: 9.2x5.9x2.8 Sonde: 11.6x3.54 (D)	 2.6 3.75	standard or rechargeable batteries	 100 20	-10 to 54	NS	any length up to 660
Hach 2100P	Turbidimeter	8.75x3.75x3.5	8	AC or 4 "AA" batteries	NS	NA	NA	NA

NA = Not applicable or not available NS = Not specified LCD = Liquid Crystal Display

TABLE 3-4 (Con't)
FIELD PARAMETERS INSTRUMENT FEATURES

Instrument	Feature					
	Readout	Datalogging Capabilities	Output	Warranty (yrs)	Options	Other Features
Current Instruments						
Hach One	LCD	NA	NA	1		Available as part of DREL2000 kit.
Hach DR2000	LCD	NA	RS232	1		colorimetric, absorptometric measurement of large range of parameters. Available as part of DREL2000 kit.
Hach Model 44600	LCD	NA	NA	1		
Alternative Instruments Evaluated						
GeoTech/Orion 250A pH meter 124 conductivity meter 820 DO meter	 LCD LCD LCD	 NA NA NA	 RS232 strip chart recorder strip chart recorder	 1 2 2		
Horiba U-10	LCD	20 samples of 6 parameters	Centronics	1		Single point calibration solution calibrates all sensors
Hydrolab Surveyor 3 (Display) H20 (Sonde)	LCD	 std: 27,200 readings ext: 59,700 readings	RS232	2	Flow cell, stirrer, internal battery charges, graphics & communication software	Sonde available in 4 different versions, display unit in 2 different versions.
QED Purge Saver	LCD	199 data sets	RS232	1		Readings can be stored, recalled, and downloaded to a computer in ASCII file. Software included at no extra charge.
Solomat WP4007 (Display) 803PS (Sonde)	LCD	50,000 readings	RS232	1	Flow cell, stirrer, ISEs	Calibration cup holds separate standards for each sensor, allowing concurrent calibration. Display unit available in 3 different versions. Sonde accepts up to 8 different sensors. Excellent software provided at cost to plot data.
Hach 2100P	LCD	NA	NA	2		

NA = Not applicable or not available   NS = Not specified   LCD = Liquid Crystal Display

Table 3-5
Instrument Specifications
Parameter: Specific Conductance

Instrument	Ranges	Accuracy	Resolution	Sensor	Temperature Compensation (degrees Celsius)	Calibration	Output Options
Alternative Instruments Evaluated							
Geotech Flow Cell/Orion 124	0 - 199.9 uS/cm 0 - 1999 uS/cm 0 - 19.99 mS/cm 0 - 199.9 mS/cm	0.5% +/- 1 digit	0.1 uS/cm 1 uS/cm 0.01 mS/cm 0.1 mS/cm	4-electrode	automatic, 0 - 35	NA	uS/cm, mS/cm
Hach 2100P	NA	NA	NA	NA	NA	NA	NA
Horiba U-10	0 - 1 mS/cm 0 - 10 mS/cm 10 - 100 mS/cm	+/- 1% of full scale	0.01 mS/cm 0.1 mS/cm 1 mS/cm	4-electrode	automatic, 0 - 50	1 point automatic 2 point manual	mS/cm
Hydrolab H20 and Surveyor 3	auto ranging 0 - 0.15 mS/cm 0.15 - 1.5 mS/cm 1.5 - 10 mS/cm 0 - 100 mS/cm	+/- 1% of range	4 digits	6-electrode	25 automatic or manual	KCl or seawater standards	uS/cm, mS/cm
QED Purge Saver	0 - 99.9 uS/cm 0 - 999 uS/cm 0 - 9.99 mS/cm 0 - 99.9 mS/cm	+/- 3% of full scale	0.1 uS/cm 1 uS/cm 0'.01 mS/cm 0.1 mS/cm	graphite, gold-plated cell	25 automatic or manual	4 point	mhos siemens uS/cm, mS/cm
Solomat 803PS and WP4007	auto ranging 1 - 1000 uS/cm 1 - 100 uS/cm	2% +/- 0.5 uS/cm 2% +/- 0.05 uS/cm	0.1 uS/cm 0.01 uS/cm	5-ring electrode	automatic 25	1 point	mS/cm, uS/cm
Current Instruments							
Hach ONE	NA	NA	NA	NA	NA	NA	NA
Hach 44600	0 - 199.9 uS/cm 0 - 1.9999 mS/cm 0 - 19.99 ms/cm,	1% +/- 2 LSD	0.1 uS/cm	Tungsten Electrode	0-100 automatic	1 point	uS/cm, mS/cm
Hach DR2000	NA	NA	NA	NA	NA	NA	NA

Notes: EG&G SOP accuracy requirement: 10%
uS/cm = microSiemens/centimeter
mS/cm = milliSiemens/centimeter
NA - Not Available.
LSD - Least Significant Digit
KCl - Potassium chloride

Table 3-5
Instrument Specifications
Parameter: Turbidity

Instrument	Ranges	Accuracy	Resolution	Sensor	Temp. Compensation (degrees Celsius)	Calibration	Output Options
Alternative Instruments Evaluated							
Geotech Flow Cell/Orion	NA	NA	NA	NA	NA	NA	NA
Hach 2100P	auto ranging 0-1000 NTU or manual 0-9.99 NTU 0-99.9 NTU 0-1000 NTU	+/- 2%	0.01 NTU on lowest range	Nephelometric	NA	Primary: Formazin Secondary: Gelex	NTU
Horiba U-10	0 - 800 NTU	+/- 3 %	1,10 NTU	Nephelometric	NA	1 point automatic, zero 2 point manual, Formazin	NTU
Hydrolab H20 and Surveyor 3	0-100 NTU 100-1000 NTU	+/- 5%	0.1 NTU 1 NTU	Nephelometric	NA	Formazin or polymer	NA
QED Purge Saver	NA	NA	NA	NA	NA	NA	NA
Solomat 803PS and WP4007	0.3-100 NTU 50-4000 NTU	5% +/ -0.2 NTU 5%+/ -20 NTU	0.1 NTU 1 NTU	Nephelometric	NA	2 point Formazin or polymer	NTU, mg/l (silica)
Current Instruments							
Hach ONE	NA	NA	NA	NA	NA	NA	NA
Hach 44600	NA	NA	NA	NA	NA	NA	NA
Hach DR2000	0 - 450 FTU	NA	NA	Absorptometric	NA	Primary: Formazin Secondary: Gelex	FTU

Notes: EG&G SOP accuracy requirement: 2 FTU
NTU = Nephelometric Turbidity Units
FTU = Formazin Turbidity Units
mg/l = Milligrams Per Liter
NA - Not Applicable.

Table 3-5
Instrument Specifications
Parameter: Dissolved Oxygen

Instrument	Range	Accuracy	Resolution	Sensor	Temp. Compensation (degrees Celsius)	Calibration	Output Options
Alternative Instruments Evaluated							
Geotech Flow Cell/Orion 820	0 - 60 mg/l 0-600% saturation	0.1 +/- 1.0% +/- 1 digit +/- 1%	3 digits	membrane polargraphic	-- auto. temp. 40 auto. press. 800-1080 mbar auto. salinity 0-40 ppt	1 point	%, mg/l
Hach 2100P	NA	NA	NA	NA	NA	NA	NA
Horiba U-10	0 - 19.9 mg/l	+/- 0.1 mg/l	0.01 mg/l 0.1 mg/l	membrane galvanic cell	0 - 40	1 point automatic 2 point manual	mg/l
Hydrolab H2O and Surveyor 3	0 - 20 mg/l	+/- 0.2 mg/l	0.01 mg/l	rebuildable polargraphic; 1 mil Teflon or LoFlow	automatic for temperature and salinity	saturated air, Winkler, or salt water	%, mg/l
QED Purge Saver	0 to 200% saturation 0-20.0 ppm 0-150% saturation	+/- 2% +/- 2 to 5% +/- 2%	0.1% 0.1 ppm 0.1%	membrane polargraphic	automatic, 0 - 50, salinity, barometric pressure	1 point barometric pressure	%, ppm, mg/l
Solomat 803PS and WP4007	0 - 20.0 ppm	+/- 0.2 ppm	0.01 ppm	rebuildable or replaceable galvanic electrode	NA	2 point	%, ppm, mg/l
Current Instruments							
Hach ONE	NA	NA	NA	NA	NA	NA	NA
Hach 44600	NA	NA	NA	NA	NA	NA	NA
Hach DR2000	0-13.0 mg/L 0-45.0 mg/L	+/- 2 mg/l	NA	AccuVac	NA	NA	NA

Notes: EG&G SOP accuracy requirement: 10%
mg/l = Milligrams Per Liter
mbar = Millibar
ppt = Part Per Trillion
ppm = Parts Per Million
NA - Not Available.

Table 3-5
Instrument Specifications
Parameter: Temperature

Instrument	Ranges (degrees Celsius)	Accuracy (degrees Celsius)	Resolution (degrees Celsius)	Sensor	Temp. Compensation (degrees Celsius)	Calibration	Output Options (degrees)
Alternative Instruments Evaluated							
Geotech Flow Cell/Orion 250A	-5 - 105	+/- 1.0	0.1	thermistor	NA	NA	C
Hach 2100P	NA	NA	NA	NA	NA	NA	NA
Horiba U-10	0 - 50	0.3	1, 0.1	thermistor	NA	NA	C
Hydrolab H20 and Surveyor 3	-5 - 50	+/- 0.15	0.01	thermistor	NA	NA	C, F
QED Purge Saver	0 - 50	1	0.1	thermistor	NA	NA	C, F
Solomat 803PS and WP4007	-20 - 70	0.15	0.1	thermistor	NA	NA	C, F, K
Current Instruments							
Hach ONE	-5 - 105	+/- 0.5	0.1	thermistor	NA	NA	C
Hach 44600	0 - 100	+/- 0.5	0.1	thermistor	NA	NA	C
Hach DR2000	NA	NA	NA	NA	NA	NA	NA

Notes: EG&G SOP accuracy requirement: 1.0 (degrees Celsius)
C = Celsius, Centigrade
F = Fahrenheit
K = Kelvin
NA - Not Available.

Table 3-5
Instrument Specifications
Parameter: pH

Instrument	Range (pH units)	Accuracy (pH units)	Resolution (pH units)	Sensor	Temp. Compensation (degrees Celsius)	Calibration	Output Options
Alternative Instruments Evaluated							
Geotech Flow Cell/ Orion 250A	-2 - 19.99	+/- 0.02	0.01	glass electrode	manual	2 or 3 point	pH, mV
Hach 2100P	NA	NA	NA	NA	NA	NA	NA
Horiba U-10	0 - 14	+/- 0.05	0.1, 0.01	glass electrode	automatic 0-50	1 point automatic 2 point manual	pH
Hydrolab H20 and Surveyor 3	0 - 14	+/- 0.2	0.01	glass pH; rebuildable or low ionic strength reference electrode	automatic	2 point	pH
QED Purge Saver	0 - 13	+/- 0.2	0.01	glass electrode	automatic	3 point	pH, mV
Solomat 803PS and WP4007	0 - 14	+/- 0.2	0.01	glass electrode	-20 to 70	2 point	pH
Current Instruments							
Hach ONE	-1.99 - 19.99	+/- 0.01	0.01	glass electrode	automatic or manual	2 point	pH, mV
Hach 44600	NA	NA	NA	NA	NA	NA	NA
Hach DR2000	NA	NA	NA	NA	NA	NA	NA

Notes: EG&G SOP pH accuracy requirement: 0.2 pH units
mV - Millivolts
NA - Not Available.

Table 3-5
Instrument Specifications
Parameter: Redox Potential

Instrument	Range	Accuracy	Resolution	Sensor	Temp. Compensation (degrees Celsius)	Calibration	Output Options
Alternative Instruments Evaluated							
Geotech Flow Cell/Orion 250 A	-1600 - 1600 mV	greater of +/- 0.2 mV or +/- 0.05 of E	0.1 mV	Platinum	NA	NA	mV
Hach 2100P	NA	NA	NA	NA	NA	NA	NA
Horiba U-10	NA	NA	NA	NA	NA	NA	NA
Hydrolab H20 and Surveyor 3	-999 - 999 mV	+/- 20 mV	1 mV	Platinum	1 point quinhydrone	NA	mV
Solomat 803PS and WP4007	-800 - 800 mV	1%	0.2 mV	Platinum	NA	NA	mV
QED Purge Saver	-500 - 500 mV	+/- 2	1 mV	Platinum	NA	NA	mV
Current Instruments							
Hach ONE	-2000 to 2000mV	0.1% +/-0.2 mV	0.1 mV (0+/- 999.9 mV) 1 mV (+/- 1,000 to +/- 1,999 mV)	Platinum	NA	NA	mV
Hach 44600	NA	NA	NA	NA	NA	NA	NA
Hach DR2000	NA	NA	NA	NA	NA	NA	NA

Notes: mV = Millivolts
NA - Not Available.

Page 6 of 6

Assessment of the various pumping systems indicated that two technologies are more suitable for the intended application at RFETS than the other four technologies being considered. The two technologies are pneumatically operated bladder pumps and electric submersible pumps. Other pumping technologies that were judged unsuitable and were not selected for the field evaluation included: jet pumps, because they rely on air lifting to operate; double piston pneumatic pumps, because they have a complex design that experience has shown is subject to malfunction; peristaltic pumps, because they are capable of lifting water only a maximum of approximately 25 feet at the 6,000-foot elevation at RFETS; and, pneumatic surface-drive piston pumps, because experience has shown that the pneumatic motors are subject to emitting a fine oily mist from air exhaust ports.

Based on the results of the assessment the following pumping systems, listed in alphabetical order, were selected for inclusion in the field evaluation:

- GeoGuard MasterFlo bladder pump;
- Grundfos Redi-Flo 2 submersible electric pump;
- Isco AccuWell bladder pump;
- Marschalk Aquarius bladder pump; and,
- QED Well Wizard bladder pump.

Of the four bladder pumps, the Geoguard and QED pumps have similar designs, while the Isco and Marschalk pumps differ from each other and from the other two in design and operation. Specifications for each of the pumps that were evaluated are summarized on Table 3-6. The general design and operation of the selected pump systems are presented in Section 5.5.3.

TABLE 3-6
PUMP SPECIFICATIONS

Manufacturer and Model	Length (in)	Diameter (in)	Weight (lb)	Materials	Pump Capacity (mL)	Maximum Lift (ft)	Power Requirements	Controller	Comments
Bladder Pumps									
GeoGuard Master-Flo	44	1.66	4.6	SS/Teflon	600	300	3.5 SCFM at 125 psi	Electric or pneumatic double-acting (fill/discharge)	Optional "cold weather blowout" removes water from discharge tubing to prevent freezing. Lifetime bladder warranty. 0.010-inch slotted intake screen.
Isco AccuWell	37	1.75	10.0	SS/Teflon	NA	250	NA, est. 3.5 SCFM at 125 psi	Electric double-acting (fill/discharge)	Elastic inner bladder allows low submergence. Pump has been discontinued by Isco.
Marschalk Aquarius	45	1.75	9.5	SS/Teflon	NA	300	NA, est. 3.5 SCFM at 125 psi	Electric or pneumatic double-acting (fill/ discharge) or triple-acting (fill/ discharge/vacuum)	Controller vacuum cycle allows low submergence. 5-year warranty on pump, 1-year warranty on controller. 18-inch-long drop tube available for extending intake below pump.
QED Well Wizard	41.14	1.50	5	SS/Teflon	NA	300	NA, est. 3.5 SCFM at 125 psi	Electric or pneumatic double-acting (fill/ discharge)	10-year warranty on pump if used with optional intake screen. Optional inlet restrictors reduce inflow rate.
Submersible Pump									
Grundfos Redi-Flo 2	11.3	1.81	5.5	SS/Teflon	NA	275	3 phase 110V or 220V, single phase 115V x 16A or 230V x 10A	Controller converts power to 3-phase 25V to 220V, at 46 Hz to 400 Hz	1-year warranty on pump and controller. Controller sensitive to exposure to water/moisture.

NOTES:
SS = Stainless Steel
SCFM = Standard cubic feet per minute
NA = Not Available

4.0 EVALUATION OF FIELD PARAMETER MEASUREMENT

Results of the evaluation of current and alternative field parameter measurement methods are presented in this section. Elements of the evaluation are a literature review, evaluation of current practices at RFETS, field evaluation, and interpretation of results.

4.1 Literature Review

Technical literature was reviewed to assess the feasibility of improving the quality of field measurement of various parameters. The purpose of the review was to establish a basis for determining the reliability of measuring certain water quality parameters in the field. The literature was reviewed in detail for field measurement of turbidity, dissolved oxygen, redox potential, alkalinity, and nitrate/nitrite as nitrogen (N). The literature related to pH, specific conductance, and temperature was reviewed only to the extent that the optimal instrumentation for those parameters would be selected for evaluation in the field.

SOP GW.05 *Field Measurement of Groundwater Field Parameters* (EG&G, 1994d) specifies the collection of pH, specific conductance, temperature, nitrate as N, and turbidity data during groundwater sampling activities. Current RFETS field practice includes measuring alkalinity and the GW.05 parameters, with the exception of nitrate as N.

Practice in the environmental industry is evolving away from the current RFETS procedure of measuring field parameters after transferring samples from the collection device to a beaker. Recent industry practice utilizes flow cells connected to dedicated purging and sampling pumps which allows continuous monitoring of parameters. Flow cells are commonly connected directly to a discharge line from a dedicated pump, thus minimizing air contact with the sample. Care must be taken to limit the above-ground length of discharge tubing, because of the potential for ambient air temperatures to heat or cool the discharged water; changes in sample temperature can potentially alter water chemistry and result in non-representative measurements of field parameters. Care must also be taken to avoid freezing water in discharge lines and flow cells during extreme cold.

Specific conductance, pH, and temperature traditionally have been monitored during well development and purging activities. These parameters, especially pH and temperature, are unstable following sample collection and are commonly measured in the field. Groundwater temperature, for example, must be measured in-situ or immediately after a sample is withdrawn from the well in order to minimize affects of ambient temperature. Because both pH and specific conductance vary with temperature, these parameters are often measured concurrently with temperature.

Dissolved oxygen, turbidity, and redox potential are also unstable and should be measured immediately after a sample is withdrawn from a well. Alkalinity and nitrate/nitrite as N are more stable and can be measured either in the field or laboratory.

4.1.1 Turbidity

The following sections provide a review of technical literature for the parameters discussed above. A brief summary of regulatory agency guidance and recommendations made in the technical literature for field measurement of each parameter is also included.

4.1.1.1 Technical Discussion

Excessive turbidity in wells may affect groundwater sample analytical results of certain organic, metallic, or radionuclide constituents. Environmental Protection Agency's (EPA) *RCRA Ground-Water Monitoring: Draft Technical Guidance* (EPA, 1992b) discourages the use of sample filtration to decrease turbidity; controlled sampling techniques are recommended instead. Therefore, the ability to accurately measure turbidity is critical to the collection of representative groundwater samples.

Turbidity measurement technology based on comparison to a formazin reference standard was first introduced in the 1950s (Hach et al., 1990). The technique of measuring turbidity using the formazin reference standard involves passing light from a known source through the sample, and measuring the amount of light that is absorbed or transmitted. The deviation of the measured value from the known formazin reference standard is represented as a turbidity reading. Units of turbidity based on the formazin standard are reported as formazin turbidity units (FTUs). This method is limited to waters with relatively low turbidities. Technology based on the principles of nephelometry has been developed to address this limitation. Nephelometry compares light transmitted through a sample to light scattered at a 90° angle (plus or minus 30°). Ratiometric nephelometry further refines measurements by including forward-scattered light in the calculation of turbidity. Units of turbidity measured by either standard- or ratiometric-nephelometry are reported as nephelometric turbidity units (NTUs) (Hach et al., 1990). Although NTUs and FTUs are considered interchangeable units, values reported by each method for any one sample may vary considerably depending upon the characteristics of the particles, and should not be considered equivalent.

Recently, the use of the formazin reference standard has been criticized, based on instability of diluted calibration solutions and on the variability of particulate size (Spair, undated). For example, 4,000 NTU calibration solutions must be prepared monthly, while dilutions for 400 NTU stock solutions are to be prepared weekly, and daily for 4 NTU solutions. Formazin is often used as the primary reference standard, while more stable Gelex secondary standards are used for routine standardization (Hach, 1992). Formazin particle size ranges from 1.75 to 20 microns (Spair, undated), making calibration to the standard problematic since light scatter varies according to particle size in addition to concentration. To address stability and particle size concerns, a polymer standard (AEPA-1) has been developed (Spair, undated). The polymer has a one-year shelf life, sub-micron particle size, and is formulated for specific instruments. The use of both formazin and polymer standards has been approved by the EPA, as described below.

EPA Method 180.1 describes turbidity measurement procedures for the turbidity range of 0 to 40 NTU (EPA, 1983). The method specifies using either of the formazin or polymer reference standards. The instrument itself should be designed so that little stray light reaches the detector. Additional design criteria include:

- Use of a tungsten lamp light source operated at a temperature of between 2,200° and 3,000° Kelvin;
- Distance traversed by incident light and scattered light within the sample should not exceed 10 centimeters (cm);
- The detector should be centered at 90° to the incident light path, not to exceed +/- 30°. The detector, and filter system if used, should have a peak spectral response between 400 and 600 nanometers (nm); and,
- Sample cells or cuvettes should be clear, colorless glass, free from scratches or fingerprints. The sensitivity of the instrument should permit detection of a turbidity difference of 0.02 unit or less in waters having turbidity of 1 NTU or less.

American Society for Testing and Materials (ASTM) Standard D-1889, *Standard Test Method for Turbidity of Water*, requires shaking the sample to disperse solids, and allowing any air bubbles to de-gas (ASTM, 1994). The sample should be diluted with one or more equal volumes of pure water until the turbidity is less than 40 NTU. The sample should then be measured against a formazin reference standard using a turbidimeter or nephelometer.

Field instrumentation available to measure turbidity includes portable turbidimeters based on the traditional laboratory instruments, and turbidimeters utilizing alternative technology. Traditional nephelometric turbidimeters are constructed to the specifications in EPA Method 180.1, and utilize a formazin primary standard and Gelex secondary standards described above. Other instruments utilize alternative technology and therefore warrant further discussion.

The alternative turbidity units utilize infrared light-emitting diodes (LEDs) for a light source, rather than tungsten lamps. The LEDs are typically pulsed to compensate for ambient light, which allows use of the unit in flow cell environments with no isolation from ambient light (traditional units require separate analysis of turbidity samples in cuvettes isolated from ambient light). LEDs are more durable and require less power for operation than tungsten light sources, making them more suitable for field use.

However, the LEDs provide light over a limited wavelength range (typically 840 to 920 nm) compared to the 400 to 1,800 nm range provided by tungsten sources. The visible light wavelength range, for comparison, is between 400 and 700 nm. Small particles are more likely to react with (absorb or scatter) light from a shorter wavelength (400 nm) than from a longer wavelength (1,800 nm). Larger particles, by virtue of their size, will react more readily with the light having a longer wavelength (Spair, undated). This characteristic of turbidimeters with LED light sources being sensitive to a narrower range of particle size than tungsten light source units can result in different readings between the methods if the predominant particle size is larger or smaller than 840 to 920 nm. Though readings may differ, neither should be considered in error, or one more correct than the other, since all methods for measuring turbidity are somewhat arbitrary techniques to quantify particulate matter in water.

Current field procedures at RFETS specify use of a Hach DR2000 spectrophotometer for measuring turbidity, as described in Section 4.2. The spectrophotometer utilizes an absorptometric method to measure turbidity and is not a nephelometric turbidimeter. Results from this instrument are given in FTU units rather than NTU units. As previously described, EPA Method 180.1 requires the use of nephelometric units.

4.1.1.2 Field Measurement

EPA (1992b) guidance recommends inclusion of turbidity in parameters monitored for stabilization during well development and purging. A well that cannot be developed to the point of producing low turbidity water (<5 NTU) may be considered by the EPA to have been improperly designed or constructed. The owner or operator of the well must demonstrate that the excessive turbidity is an artifact of the geologic materials; otherwise, the EPA can require redrilling of the well.

EPA Region VIII guidance (1994a and 1994b) for EPA project managers conducting hydrogeologic investigations requires monitoring turbidity when developing and purging wells. The following text indicates the importance the EPA places on monitoring turbidity during development:

> "Turbidity <u>must</u> be monitored during development and <u>must</u> stabilize before development is deemed complete. The goal for development is to reach a level of 5 NTU turbidity during subsequent purging for sampling... Turbidity is the best indicator of adequate well development, and is, therefore, the most critical parameter to monitor."

The acceptable range for demonstration of turbidity stabilization is 5 NTU plus or minus 5 NTU (EPA, 1994b). This implies that a turbidity value of 10 NTU is acceptable. For the purposes of this project, the 5 NTU goal was used. Advance approval for variance from the 5 NTU standard must be obtained from the EPA project manager. If a higher turbidity value is approved, the criteria for adequate development is turbidity stabilization within a 20 percent range.

Historically, highly turbid samples have been addressed by filtering samples with 0.45-micron filters. However, EPA guidance discourages the use of filtration (EPA, 1992b). Agency guidance is based on research indicating that hazardous constituents may be mobile in the subsurface in both the dissolved and solid phases. Filtering samples is contradictory to the goal of obtaining groundwater samples representative of formation conditions. Numerous studies (e.g., Puls, 1994b; Kearl et. al., 1993; Barcelona et. al., 1994) recommend the minimization of turbidity in well purging and sampling through carefully controlled pumping. See Section 5.5 of this report for further discussion of purging and sampling methodologies intended to minimize turbidity in groundwater samples.

When measuring turbidity in glass cuvette sample bottles, as is done with the Hach DR2000 spectrophotometer and 2100P turbidimeter, it is critical to maintain the cuvettes scratch free and scrupulously clean. Fingerprints and other residue on the exterior of the cuvette can affect readings. Additionally, the cuvettes should be indexed to a specific meter; slight variances in optical clarity of the glass or in light source degradation can alter turbidity readings. Indexing the cuvettes regularly minimizes this impact by calibrating the instrument to a particular cuvette placed in the instrument in a consistent direction.

4.1.2 Dissolved Oxygen

4.1.2.1 Technical Discussion

Dissolved oxygen (DO) is often the principal oxidizing chemical component of groundwater and is therefore a critical parameter in controlling the mobility of electrochemically sensitive metals and radionuclides in groundwater (White et al., 1990). Increased DO levels can oxygenate Fe^{++}, forming Fe^{+++} colloids (Liang et al., 1993). Dissolved oxygen levels should be measured in the field due to the potential for rapid degassing or oxygenation of the sample on contact with the atmosphere. Ambient temperature, barometric pressure, and salinity also can affect dissolved oxygen levels.

Rose and Long (1988) found that DO concentrations can be measured precisely in the field by titration or electrode methods. Under field conditions, both the precision and detection limits of these methods are approximately 0.2 mg/L. However, according to Rose and Long (1988), the natural variability of DO concentrations at a given well might be appreciably higher, approximately +/- 0.5 mg/L about a given mean. Rose and Long state that adequate sampling procedures involve collection of samples at discrete depth intervals at ambient temperature and pressure, and isolation of groundwater from the atmosphere. They found nitrogen displacement, gas-driven piston pumps, and modular/positive pressure systems "conditionally acceptable" methods to collect samples for DO measurement. Bailers and suction lift pumps were identified as generally unacceptable sampling methods.

White et al. (1990), on the other hand, found that there are no adequate sample collection methods to accurately measure DO at low levels. According to White, titration and oxygen-sensitive membrane electrodes do not attain sufficiently low detection limits. Additionally, titration is not generally suitable for field use, and the use of electrodes is problematic since electrodes must be calibrated against air-saturated dissolved oxygen and corrected for barometric pressure, temperature, and salinity. White developed a downhole sampling device that mixes a groundwater sample in an ampule containing a reagent, which decreases the DO detection level by an order of magnitude relative to the electrode and titration methods. Reagent ampules are not easily adaptable to ex-situ flow cell field parameter measurement (see Section 4.4.1.2) and generate waste, conflicting with EG&G's waste minimization goal.

4.1.2.2 Field Measurement

The EPA (1992b) recommends inclusion of DO in parameters monitored for stabilization during well purging; however, no requirement for specific measurement methodology is provided. EPA (1994b) Region VIII *Standard Operating Procedure for Well Purging* also recommends, but does not require, monitoring DO during purging.

For laboratory measurement of DO, EPA Methods 360.1 and 360.2 describe electrochemical probe and titration techniques, respectively. Method 360.1 states that "[i]nterfacial dynamics at the probe-sample interface are a factor in probe response and a significant degree of interfacial turbulence is necessary. For precision performance, turbulence should be constant" (EPA, 1992c). A detection limit of 0.05 mg/L is identified for this method. No detection limit for titration (Method 360.2) is provided. ASTM Standard D888 and American Public Health Association (APHA) Method 4500-O both reference titration and electrochemical probe techniques (ASTM [1992]; APHA [1992]).

4.1.3 Redox Potential

4.1.3.1 Technical Discussion

Oxidation and reduction reactions (or, redox potential) mediate the behavior of many chemical constituents in groundwater (Greenberg et al., 1992). Redox potential is commonly designated Eh, emphasizing the transference of electrons to and from oxygen during the reaction. The reactivities and mobilities of important metallic elements depend strongly on redox conditions. Chemical reactions in groundwater often can be characterized by pH and Eh together with the activity (concentration) of dissolved chemical species (Greenberg et al., 1992). Eh values can be calculated using the Nernst equation and known aqueous concentrations of various redox couples (Walton-Day et al., 1990). Ionic species in groundwater are typically associated as redox couples such as iron (Fe^{++} and Fe^{+++}) and manganese (Mn^{++} and Mn^{+++}).

Groundwater Eh in some cases shows an approximate inverse relationship with pH, but is hard to interpret in terms of redox couples present (Olie et al., 1992). Redox potential is also closely associated with dissolved oxygen content of the water (Liang et al., 1993). Mobilization of the redox couples to and from dissolved and solid phases results from a complex interaction of the couples, pH, and Eh.

The complexity of the interactions results in poor correlations between the calculated Eh values from the redox couples present and the Eh values obtained from field measurement instrumentation (Greenberg et al., 1992). Measured values are obtained by using platinum or wax-impregnated graphite (WIG) electrodes (Walton-Day et al., 1990). Interferences in field measurement of redox potential include poisoning of platinum electrodes, lack of electrochemical equilibrium in natural systems, and lack of internal equilibrium and the consequent measurement of mixed potentials (Walton-Day et al., 1990). In particular, platinum electrodes may be poisoned by exposure to measurable levels of oxygen: Walton-Day et al., (1990) found variances as much as several hundred millivolts between new and used platinum electrodes. These researchers also reported that WIG electrodes displayed a non-reproducible sensitivity to dissolved organic matter. Greenberg et al. (1992) also identified limitations of electrode measurement of Eh, including irreversible reactions, electrode poisoning, the presence of multiple redox couples, very small exchange currents, and inert redox couples.

4.1.3.2 Field Measurement

Problems discussed in the previous section limit the usefulness of redox potential field measurements. Regulatory agency guidance provided by the EPA (1992b) lists Eh as an unstable parameter suitable for field measurement, but does not require its field measurement. EPA methods for Eh measurement were not identified in literature reviewed for this report.

Walton-Day et al., (1990) recommends use of a flow cell for monitoring Eh in addition to other field parameters. Sample water from wells, routed through a flow cell to minimize air contact, increases the potential for accurate Eh and DO measurement. In addition, Walton-Day et al., (1990) recommend that platinum electrodes be stored in oxygen-scavenging solution and be routinely replaced after exposure to water containing oxygen. WIG electrodes should be replaced on a daily basis.

Olie et al. (1992) tested an in-situ device to measure field parameters. The device was found to be suitable for vertical profiling of certain field parameters, including Eh.

4.1.4 Alkalinity

4.1.4.1 Technical Discussion

Total alkalinity is defined as the molar equivalent sum of all bases that are titratable with a strong acid (Drever, 1988), and is a measure of the capacity of water to neutralize acids. In most natural waters, including waters at RFETS, bicarbonate and carbonate ions are far more abundant than other bases and contribute almost all of the alkalinity. The term "carbonate alkalinity" is defined as the molar equivalent sum of all carbonate (CO_3) and bicarbonate (HCO_3) ions and is generally numerically equivalent to total alkalinity. Alkalinity of a natural water is related to the pH and the dissolved CO_2 present in that water. Waters with high total alkalinity have the ability to buffer or neutralize large quantities of acid. The addition of acid to waters with high total alkalinity will not significantly lower the pH until all the alkalinity is consumed.

4.1.4.2 Field Measurement

Alkalinity may be measured by titration or spectrophotometric methods. Electrochemical probes for field measurement of alkalinity are not commercially available (Garner, 1988). Total or carbonate alkalinity can be measured in the field by titration with an acid and a pH-sensitive indicator compound. In field titration, acid is progressively added to a water sample until the alkalinity is consumed. When the alkalinity is consumed, the pH of the sample can drop rapidly, changing the color of the indicator compound. The total alkalinity of the water sample then can be calculated based on the amount of acid that was added to the water sample. Field titration of alkalinity is relatively easy and inexpensive, but has the potential to generate waste. Dependable transducers for field measurements of total or carbonate alkalinity are not available (Garner, 1988). Alkalinity does not rapidly change if field samples are handled properly, and can be easily and accurately measured as a laboratory parameter.

4.1.5 Nitrate/Nitrite as Nitrogen

4.1.5.1 Technical Discussion

Nitrogen in natural waters can be found in several forms such as dissolved nitrogen gas (N_2), nitrate (NO_3^-), nitrite (NO_2^-), nitrous oxide (N_2O), ammonium (NH_4^+), and dissolved organic nitrogen. Nitrate is a very common form of nitrogen found in groundwater and is important because in sufficient quantities nitrate can be toxic to humans (i.e., can cause methemoglobinemia and cancer [NIOSH 1990]. Elevated nitrate concentrations can cause the eutrophication of surface waters, algae blooms, and can be toxic to fish.

Anthropogenic sources of nitrogen to groundwater include agricultural activities such as feedlots and the application of fertilizers, contamination by sewage, some industrial processes, and precipitation of airborne nitrates. Nitrates in groundwater systems also can occur naturally by the fixation of nitrogen gas by certain plants. However, almost all elevated concentrations of nitrate in groundwater systems can be traced to anthropogenic influences.

In reduced (low dissolved oxygen) groundwater, the eventual fate of most nitrogen compounds is either 1) ammonification (conversion to ammonia) and subsequent adsorption onto aquifer material, or 2) denitrification (conversion to nitrogen gas) and subsequent degassing into the unsaturated zone. In either case nitrogen is removed from the groundwater. In oxidized groundwater the eventual fate of nitrogen compounds is conversion to nitrate, which can persist for a relatively long time and is easily transported in groundwater.

Nitrate and nitrite are both oxidized ions commonly found in groundwater. Nitrite is slightly less oxidized than nitrate and is less stable. Since nitrate and nitrite behave similarly in groundwater, both are derived from similar sources, and nitrite readily decays into nitrate, these ions are often reported together as nitrate and nitrite as nitrogen (nitrate/nitrite as N).

4.1.5.2 Field Measurement

Current EPA methods for measuring nitrate/nitrite as N in the field are based on colorimetric analysis. A water sample in the field can be mixed with a reagent and analyzed in a spectrophotometer. Field colorimetric methods are relatively reliable and inexpensive, but due to the use of a reagent containing cadmium, have the potential to generate waste during the sample analysis and decontamination procedures. Ion-specific electrodes (ISEs) are also available for nitrate/nitrite as N measurement. If proper sample handling and laboratory procedures are used, nitrate/nitrite as N can be accurately measured as a laboratory parameter.

4.2 Current Practice at RFETS

Procedures for measuring field parameters when developing or purging groundwater monitoring wells are provided in GW.05 *Field Measurement of Groundwater Field Parameters* (EG&G, 1994d). The following field parameters are listed in GW.05 for field measurement during well purging and sampling:

- pH;
- Specific Conductance;
- Temperature;
- Nitrate as Nitrogen;

- Nitrite; and,
- Turbidity.

It should be noted that the list does not accurately reflect current field practice. Parameters currently measured in the field are pH, temperature, specific conductance, total alkalinity, and turbidity. Nitrate and nitrite have been eliminated from the field parameter list to comply with RFETS goal of waste minimization.

Specified instruments (in GW.05) utilized to measure field parameters include the Hach One pH meter, Hach DR2000 spectrophotometer, Hach Model 44600 Conductivity/Total Dissolved Solids (TDS) meter, Orion Total Alkalinity test kit, and a standard thermometer. The Hach One and DR2000 instruments are available in a single kit from Hach as the DREL2000 environmental laboratory. Procedures provided in GW.05 follow those specified by the instrument manufacturers.

Generally, samples for field parameter measurement are collected during well development and purging activities at one-half casing volume intervals. The samples are poured from bailers into clean plastic or glass beakers. A portion of the sample is poured into a clean cuvette for turbidity measurement in the Hach DR2000 spectrophotometer. The remaining sample is utilized for measuring temperature, conductivity, and pH, in that order. Temperature is measured first due to the potential for rapid change. Specific conductance is measured second due to potential interference from pH electrolyte reference solution, and pH is measured last. A Hach Model 44600 Conductivity/TDS meter is used to measure specific conductance; a Hach One portable meter is used for measuring pH and temperature parameters. These instruments are calibrated twice daily utilizing commercial laboratory-prepared calibration solutions. The spectrophotometer is utilized for measuring the sample turbidity. The spectrophotometer is calibrated on a quarterly basis using the formazin reference standard. Based on the manufacturer-specified 48-hour shelf life, the formazin reference standard is difficult to use for daily calibrations. The more stable Gelex (secondary) standard is used for daily calibration.

Alkalinity is measured once during well development and purging, using the Orion Total Alkalinity test kit and the procedure is described in Section 4.1.4.2.

4.3 Field Evaluation

A field evaluation of a variety of alternative instruments was conducted concurrently with the well sampling field evaluation program described in Section 5.5.3. The alternative instruments were compared to instruments currently used in the program (as described above) based on considerations of instrument suitability and on the analysis of field monitoring results.

Instrument suitability criteria factors considered in the evaluation were:

- Ease of use, calibration, and maintenance;
- Adaptability to use with a flow cell;
- Multiparameter capability;
- Electrical power requirements;
- Data logging capability;
- Ambient temperature operating range;
- Durability; and,
- Regulatory agency acceptance of specifications and design.

The evaluation included comparison of measurements between alternative instruments and the instruments currently used in the groundwater monitoring program. In addition to the field evaluation (Section 4.3.2), the performance of the instruments was compared in bench test. A description of the bench test is presented in Section 4.3.3.

4.3.1 Instrument Description

The design and basic features of each instrument that was evaluated are described in the following sections.

4.3.1.1 GeoTech/Orion

The GeoTech/Orion unit is comprised of a flow cell manufactured by GeoTech and field parameter instrumentation manufactured by Orion. The flow cell consists of a 240-milliliter (ml) polycarbonate body through which water is directed during pumping activities. A valve upstream of the flow cell allows water to be diverted from the flow cell for sample collection, avoiding interference from any electrode fluids. Electrodes are inserted individually into the top of the cell, through a number of access ports. Water is introduced into the flow cell from the bottom, circulated past the probes, and discharged out the top of the cell for disposal. Field parameters are measured by a set of three separate Orion instruments, which monitor pH, temperature, specific conductance, DO, redox potential, and TDS. Although Orion instruments were supplied with the Geotech Flow cell, other instruments could be used for parameter measurements. The access ports on the flow cell have a range of diameters and are intended to accommodate most single parameter water quality sensors available on the market.

4.3.1.2 Horiba U-10

The Horiba U-10 is a multiparameter instrument consisting of a sonde (a multichannel probe unit), communication cable, and display unit. The sonde includes probes which monitor pH, temperature, specific conductance, DO, turbidity, and salinity. The turbidity sensor utilizes the pulsed infrared light technology discussed in Section 4.1.1.1. The unit features "single point" calibration fluid, which calibrates all probes simultaneously. The more rigorous two point calibration requires separate calibration fluids for each sensor. The communication cable is available in 2- and 10-meter lengths, the latter being waterproof for remote measurements. However, since the sonde has a diameter of approximately four inches, remote measurements with this instrument are not possible in monitoring wells having a four-inch or smaller inside diameter. The display unit is a handheld device that displays each parameter separately. The unit features limited data logging capabilities (maximum 20 measurements) and can be connected to a printer for downloading.

4.3.1.3 Hydrolab H20

The Hydrolab H20 is also a multiparameter instrument that includes probes for measuring pH, temperature, specific conductance, DO, turbidity, redox potential, and TDS. A water level sensor is available if the unit is used for remote measurement. The turbidity sensor utilizes pulsed infrared light source technology and may be calibrated to formazin or polymer reference standards. The redox sensor utilizes a platinum electrode. A 270-ml flow cell is available as an option, as is an external stirrer. The flow cell attaches directly to the sonde providing a means for water to flow past the probes; the stirrer ensures a constant mixing of water in stagnant conditions and is not designed for use with the flow cell. The sonde-to-datalogger cable is available in any length up to 150 meters. The sonde is also available in a 1.75-inch diameter "downhole" version for in-situ monitoring with an appropriate length cable. Two display modules are available: the "Scout" display module displays up to six parameter measurements simultaneously, and the "Surveyor" unit which also displays all parameters simultaneously but includes datalogging capabilities and an RS-232 interface port for electronic transfer of data. Up to 70,000 measurements can be stored by the surveyor datalogger.

4.3.1.4 QED Purge Saver

The QED Purge Saver is a multiparameter instrument similar to the Horiba unit and includes a 240-ml flow cell. The sonde probes measure pH, temperature, specific conductance, DO, and redox potential. The display module provides simultaneous readout of all parameters. The unit includes moderate datalogging capabilities (maximum of 199 sets of measurements can be stored) and an RS-232 interface port for computer communication of ASCII files.

4.3.1.5 Solomat 803PS

The Solomat 803PS is similar to the Hydrolab H20. The sonde for the Solomat unit includes probes for measuring pH, temperature, specific conductance, DO, turbidity, redox potential, ammonia, and TDS. The redox potential sensor, available as an option, was not included in the field evaluation unit. A water level sensor is also available. The turbidity sensor for this unit features a pulsed infrared light source. The redox sensor utilizes a platinum electrode. A flow cell is available as an option, as is an integrated stirrer. Communication cables for this instrument are available in any length up to 660 feet. Two display modules are available for this unit. The WP803 provides simultaneous readout for all parameters and datalogging capabilities. The WP4007 display unit includes simultaneous readout and datalogging capabilities, and includes ports for four additional electrodes. The WP4007 display unit was used in this field evaluation. Up to 50,000 readings can be stored in the WP4007 memory.

4.3.1.6 Hach 2100P

The Hach 2100P is a single-parameter portable turbidimeter. The unit is similar in design to Hach laboratory instruments and is designed to meet the instrument design criteria specified in EPA Method 180.1. Samples are collected in indexed glass cuvettes, and placed in a sealed compartment for measurement. The instrument utilizes ratiometric nephelometry to measure turbidity. The unit provides data via a digital readout; no datalogging capabilities are provided.

4.3.2 Field Test

A field test was conducted in order to assess the capabilities of the alternative instruments in improving field parameter measurement in the Groundwater Monitoring Program. The field test was conducted concurrently with the groundwater purging and sampling field evaluation described in Section 5.5.3, and followed the essential procedures of current field parameter measurement practice. Current field parameter instruments were included in the evaluation to provide a comparison with current RFETS procedures and technologies.

The field evaluation was conducted during June and July, 1994. The field tests were conducted at four groundwater monitoring wells selected according to the criteria described in Section 3.2. Each instrument was assigned to a specific groundwater purging and sampling pump unit. The combined pumping/instrumentation systems were rotated between the four selected groundwater monitoring wells during the test period. Accordingly, each instrument was used a minimum of four times, and was evaluated against other alternative instruments. Turbidity was measured during each test using the assigned multiple parameter instrument, the Hach 2100P turbidimeter, and Hach DR2000 spectrophotometer. Thus, it was possible to simultaneously monitor turbidity with the alternative sensor, the EPA-approved design, and the instrument that is currently used in the groundwater monitoring program. Field crews recorded judgements of instrument suitability and quantitative monitoring results.

4.3.3 Bench Test

A bench test was conducted at the conclusion of the field test. The objective of the bench test was to compare the instruments against a single sample for pH, specific conductance, turbidity, DO and redox potential. Instruments were calibrated by the methods used during the field evaluation. The sample consisted of approximately 400 ml of 0.1-molar KCl mixed with approximately 3,500 ml of deionized water. A separate set of turbidity samples was prepared by diluting formazin concentrate to a 25-NTU solution, and various solutions of premixed polymer standards. Each instrument was used to monitor field parameters with splits of the sample water. Calibration was verified at the conclusion of the test, and a sample split was sent to an RFETS contract laboratory for pH and specific conductance analysis.

4.4 Interpretation of Results

4.4.1 Instrument Suitability

The suitability criteria identified in Section 4.3 were used to evaluate each instrument during the field test. The evaluation results described below are summarized in Table 4-1.

TABLE 4-1
FIELD PARAMETER INSTRUMENT ADVANTAGES AND LIMITATIONS

Instrument	Advantages	Limitations
Current Instruments		
Hach One	Measures pH and temperature. Easy to use and calibrate. Probe is easy to change. Could be adapted to GeoTech flow cell.	pH probe fouls easily. Only measures 2 parameters. No flow cell or datalogging capabilities.
Hach DR2000	Measures large range of parameters. Easy to calibrate with premixed reagents.	Measurement method is AccuVac or titration for many parameters; vials and reagents become waste materials. Absorptometric measurement for turbidity is not EPA- approved, and is unreliable. No datalogging or flow cell capabilities.
Hach 44600	Measures TDS, specific conductance, temperature. Easy to use and calibrate. Probe is easy to change. Could be adapted to GeoTech flow cell.	Only measures 3 parameters. No datalogging or flow cell capabilities.
Alternative Instruments Evaluated		
GeoTech/Orion	Design facilitates individual component replacement as necessary. Only pH probe needs calibration. Flow cell easy to use and can be adapted to many other probes.	Assembly of flow cell required. No datalogging. 3 separate meters, 5 separate probes. No turbidity measurement. Redox potential and pH probes require periodic electrolyte filling.
Horiba U-10	Single point automatic calibration is easy. DO, pH, and reference probes field replaceable. Logs up to 20 data sets.	Two-point manual calibration is time-consuming. Other probes need to be replaced by factory. No flow cell. Limited manual logging only, downloads to printer only. AEPA-1 polymer turbidity standard is not available.

TABLE 4-1 (Con't)
FIELD PARAMETER INSTRUMENT ADVANTAGES AND LIMITATIONS

Instrument	Advantages	Limitations
Hydrolab H20 and Surveyor 3	Calibration is simple. DO sensor membrane is field replaceable. Cleaning is only regular maintenance necessary. Flow cell is easy to use. Extensive datalogging capabilities, can be downloaded to printer or computer. AEPA-1 polymer turbidity standard is available.	Calibration uses significant volume of standards. Calibration must be within range of expected measurements. Flow cell is clear and must be shielded from ambient light when measuring turbidity. Requires a program such as Procomm to download to a computer.
QED Purge Saver	Calibration is straight forward. pH electrode can be field replaced. Flow cell is easy to use. Moderate datalogging capabilities (199 data sets). Data easily downloaded to ASCII file.	Calibration requires 3 point slope for pH, 4 point slope for conductivity. DO calibration requires air saturated DI water and ambient barometric pressure. DO membrane requires periodic replacement.
Solomat 803PS and WP4007	All probes except temperature field replaceable. DO probe available in rebuildable or replaceable versions. Flow cell is easy to use. Extensive logging capabilities with downloading to computer, modem, or printer. Software package allows export to Lotus or ASCII file. Extensive graphing capabilities. Additional ISEs may be added to display module. AEPA-1 polymer turbidity standard is available.	All parameters except temperature require 2 point calibration, bracketing expected values. Requires familiarity with control box, and use of identical reference standards. Flow cell inlet and outlet ports are at bottom of cell, and don't allow probe immersion unless outflow is restricted or unit is inverted. Ambient light can interfere with turbidity, but less so than with Hydrolab unit.
Hach 2100P	Accurate and repeatable turbidity measurements. EPA-approved methodology. Simple to operate. Primary calibration only necessary quarterly; secondary calibration on daily basis. AEPA-1 polymer turbidity standard is available.	Only measures 1 parameter. Requires formazin dilution for primary calibration. Requires scrupulously clean and scratch-free indexed cuvettes. No flow cell or datalogging capabilities.

4.4.1.1 Ease of Use, Calibration, and Maintenance

The GeoTech/Orion unit consists of separate probes for each parameter, cables, and three instruments. Each parameter is read individually, and the unit includes no datalogging capabilities, although the pH meter includes an RS-232 port for computer communications. Orion, the instrument manufacturer, states that only the pH electrode needs calibration. Standard pH slope calibration with pH 4, pH 7, and pH 10 buffers is required. Probes must be cleaned on a regular basis, and the pH and redox electrodes must be filled with electrolyte solution periodically. Because the probes are separate assemblies, they can be replaced easily. Instrument response time is generally less than 1 minute.

The Horiba U-10 multiparameter unit is simple to use. The unit may be single-point calibrated with a single calibration solution; dual-point slope calibration is more time consuming but provides greater accuracy. The AEPA-1 polymer turbidity standard is not currently available for this instrument. The DO, pH, and reference sensors are removable for replacement; other sensors must be replaced by the manufacturer or distributor. The instrument manually logs up to 20 sets of measurements. As currently configured by the manufacturer, data can only be downloaded to printers with Centronix connectors. However, modification may be possible to download to any printer or a computer. Instrument response time is generally less than 1 minute. The manufacturer reports that up to 2 minutes may be required for DO response.

The Hydrolab H20 multiparameter unit is also simple to use. Calibration is a simple but time-consuming process; each sensor must be calibrated individually with reference standards. The AEPA-1 polymer turbidity standard is available for this instrument. Probes are not field replaceable, with the exception of the DO sensor membrane. The sonde was used with a Surveyor 3 display module, which has extensive datalogging capabilities. Data can be downloaded to a printer or computer with appropriate software, which is available from Hydrolab. Instrument response time is reported by the manufacturer as less than 1 minute.

The QED Purge Saver unit is easy to use in the field. Calibration is simple but is the most time-consuming of the units evaluated. Three reference standards are required for pH calibration, and up to four reference standards are required for specific conductance calibration. DO calibration requires the use of air-saturated deionized water and ambient barometric pressure adjusted for altitude. The specific conductance and temperature probes can be replaced only by the manufacturer; the pH electrode is field-replaceable. The DO electrode membrane must be replaced periodically. The Purge Saver datalogger can store up to 199 sets of measurements, and can be easily downloaded to an ASCII file with a QED-supplied program. Instrument response time is generally less than 1 minute.

The Solomat unit operates and calibrates in a similar manner as the Hydrolab. A two-point calibration method is used; reference standards must bracket expected measurement ranges. The AEPA-1 polymer turbidity standard is available for this instrument. All probes except the temperature thermistor are field-replaceable. The WP4007 display module has extensive datalogging capabilities, and data may be downloaded to a printer, modem, or computer. The software included with the unit allows export of stored results to a number of different file formats. Graphing capabilities are also part of the package. Instrument response time is generally less than 1 minute.

The Hach 2100P turbidimeter is a single-parameter instrument. The system requires maintenance of scrupulously-clean and scratch-free glass cuvettes, which must be individually calibrated and indexed to a specific instrument. Checking calibration is simplified by using Gelex secondary standards. The AEPA-1 polymer turbidity standard may also be used with this instrument. Accurate calibration with formazin primary standards requires careful dilution and handling. The instrument is easily maintained, but has no datalogging or downloading capabilities. The instrument provides a turbidity value within 11 seconds of measurement.

Of the instruments currently used in RFETS groundwater monitoring program, the Hach One meter measures pH and temperature. The Model 44600 meter measures conductivity, TDS, and temperature. The DR2000 measures a number of parameters using colorimetric titration methods. None of the Hach instruments include datalogging or flow cell features. Probes from the Hach One or Model 44600 could be adapted to the GeoTech flow cell. These instruments generally provide measurement values within 1 minute.

4.4.1.2 Adaptability to Flow Cells

The GeoTech flow cell unit is easy to use, but requires assembly. Pump discharge lines are easily connected directly to the flow cell. A flow cell is not available from Horiba for the U-10 instrument, although a cell is reportedly under development by the manufacturer. The Hydrolab manufacturer-supplied flow cell for the H20 system is easy to attach and use; however, the turbidity sensor is sensitive to ambient light and the flow cell must be covered for accurate readings. The QED Purge Saver flow cell is like the GeoTech cell in that there is no option for a stirring propeller. The manufacturers of both flow cells state that complete mixing and full flow-through exchange of sample is attained by the configuration of the cells, the probes, and the location of the inflow and outflow ports. The Solomat unit flow cell is similar to the Hydrolab design, except that inlet and outlet ports are located at the bottom of the cell, minimizing contact of probes with the water sample unless it is inverted or outflow is regulated. An optional built-in stirrer improves flow over the electrodes. This unit is also affected by ambient light interference, but less so than the Hydrolab unit. The Hach 2100P is not adaptable to a flow cell due to the design of an integrated cuvette holder and sensor within the body of the instrument.

4.4.1.3 Multiparameter Capability

All units except the Hach 2100P turbidimeter are multiparameter to some extent. The capabilities of each instrument are summarized in Section 4.3.1 and Table 3-3.

4.4.1.4 Electrical Power Needs

All evaluated instruments are battery powered, with either rechargeable or replaceable batteries. Rechargeable battery units are supplied with an ac-powered recharger unit. Rechargeable battery life varies from 8 to 24 hours, according to manufacturer specifications. Replaceable battery life ranges from about 100 to about 200 hours. Instrument power requirements are listed in Table 3-4.

4.4.1.5 Datalogging Capabilities

Datalogging capabilities of the evaluated instruments vary considerably. The Orion instruments used in the GeoTech flow cell do not include any data storage capabilities, although they may be connected to a computer or strip chart recorder for real-time data transfer. The Horiba U-10 logs up to 20 data sets. The Hydrolab Surveyor 3 display unit logs up to 9,000 data sets. The QED Purge Saver logs 199 data sets. The Solomat WP4007 display unit logs up to 6,000 data sets. The Hach 2100P has no datalogging or data transfer capabilities.

4.4.1.6 Ambient Temperature Operating Range

All instruments operate within a minimum temperature range of 0° to 40°C, with the exception of the Orion pH meter which has a minimum operating temperature of 5°C. The Hach One, Hach Model 44600, and Orion DO instruments have a maximum operating temperature of 50°C. The Solomat unit operating temperature range is -10° to 54°C. It is likely that winter temperatures will occasionally be lower than the recommended minimum operating temperatures of the instruments. Consequently, care should be taken to protect the instruments during the coldest winter conditions.

4.4.1.7 Durability

Given the relatively short two-week field evaluation, testing for durability was not part of this evaluation. However, the conclusions drawn through observations during the field evaluation are that each unit is designed for field application and appears sufficiently durable for its intended use.

The Orion pH meter, Solomat, and QED Purge Saver instruments are warranted by the manufacturers for one year. The Orion conductivity and DO meters, the Hydrolab H20, and the

Hach turbidimeter are warranted for two years. The probes or sensors for each instrument typically carry separate warranties that are generally shorter than those for the instruments.

4.4.1.8 Regulatory Agency Acceptance

All field measurement methods except turbidity utilize technology approved by regulatory agencies. As discussed in Section 4.1.1.1, current EPA turbidity measurement methods specify certain design criteria which are not met by instruments utilizing LED technology. The Hach 2100P uses the approved technology. It should be noted that the LED technology is approved and recommended by the International Standards Organization (ISO) in standard 7027 (ISO, 1990). It is not clear at this time if EPA methods will be revised to include the ISO recommendation for allowing LED technology for turbidity measurement.

Instrument accuracy and range requirements are not specified by agency regulations. RFETS accuracy requirements, provided in footnotes to Table 3-5 for each parameter, are met by all instruments except turbidity. RFETS SOP accuracy requirement for turbidity is +/- 2 FTU, while instrument accuracies are generally specified by the manufacturer as a percentage of the instrument's turbidity measurement range. For example, the Hach 2100P accuracy is specified as +/- 2 percent of range. This instrument provides three ranges: 0-9.99, 0-99.9, and 0-1,000 NTU. Accuracy for each range is +/- 0.2 NTU, +/- 2 NTU, and +/- 20 NTU, respectively. Only the lower two of the three instrument ranges are within the SOP accuracy requirement. Other instruments provide similar accuracies, and none are completely within the SOP requirement.

4.4.2 Instrument Performance

Data collected during the field tests and bench tests are tabulated in Appendices A-1.1 and A-1.2, respectively. Appendix A-2.1 includes plots of the field parameter data collected during the four-well purging and sampling field evaluation. Instrument comparisons are shown by parameter at each well. Each instrument was used in wells pumped at different times and at different flow rates using four different pumps and a bailer. As such, the plotted data provide qualitative comparisons of the performance of each instrument. In addition, differences in the accuracy of daily calibrations can add an element of variability to the field data. A more definitive comparison was conducted using a bench test under controlled test conditions (Appendix A-2.2). Conditions were controlled by conducting measurements inside the groundwater field trailer over a short time period using splits of a single batch of prepared water. The results of that bench testing are described along with the results of the field evaluation.

The plots in Appendix A-2.1 are grouped by parameter and well. Each plot presents the measurements by all the instruments used for a particular parameter at a given well. Since four wells were tested, there are four plots for each parameter plus two sets of additional plots comparing turbidity measurements in each well using the Hach DR2000 spectrophotometer and the Hach 2100P turbidimeter. The two Hach instruments were used to provide a common basis for comparing the different tests, and to compare the instrument currently used in the groundwater monitoring program (DR2000) against the alternative multiparameter turbidity measurements and the specialized single-parameter 2100P turbidimeter.

The following observations can be made from the plots of the field evaluation in Appendix A-2.1 and from the data resulting from the bench test presented in Appendix A-2.2.

4.4.2.1 pH

All instruments produced similar pH measurements for a given well for the pumped tests. Values for the pumped tests ranged plus or minus approximately 0.1 pH unit from the averages. During the bailed test, large differences were seen for the pH values measured for three of the four wells (Wells 1786, 2587, and 41691). In those three wells pH was measured at 8 to 9, approximately 1 to 2 pH units higher than the values measured by all instruments during the pumped tests. Though each of the high readings was measured by the Horiba instrument, the cause for the abnormal values is likely due to the sampling method. The results of the bench test show that the Horiba gave the lowest pH reading (see plots in Appendix A-2.2), suggesting that the high values registered by that instrument during the field evaluation may have been a result of the entrainment of sediment in groundwater samples during the process of bailing.

The bench test results indicate measured pH ranges from a high by the Hydrolab instrument of 6.12 to a low by the Horiba instrument of 5.07. The average of the instruments was 5.79. An aliquot of the prepared sample of water used for the pH bench test was analyzed by an EG&G contract laboratory. The laboratory reported a pH of 5.52; somewhat below the average value measured by the instruments. The difference between the instrument measurements and the laboratory-measured value ranged from a high of 9.8 percent for the Hydrolab instrument, to a low of 4.2 percent for the Hach instrument. The Orion and QED instruments also compared well at 4.7 percent and 6.4 percent, respectively. The instrument average was 4.7 percent above the laboratory value.

4.4.2.2 Dissolved Oxygen

The plots in Appendix A-2.1 readily demonstrate the problem with measuring DO in the field. The range in values measured by the different instruments deviated from the average value by the magnitude of the average at any point in time during pumping. For example, the average value in Well 2587 test after 14 minutes of pumping was approximately 10 mg/L, and the range of values was approximately 5 to 15 mg/L. The ranges measured in the other wells was similarly large.

A notable observation is that although higher DO values from samples collected with a bailer would be expected, the DO values measured with the Horiba during the bailed tests were not higher than the values measured during the pumped tests. There is no ready explanation for this result since the bench test results shown in Appendix A-2.2 indicate that the Horiba gave slightly higher than average readings (6.06 mg/L versus the average of 5.35 mg/L). The fragility of the membrane, and the sensitivity to its manual, rubber-band method of attachment to the sensor tips, make field DO measurements subject to high degree of uncertainty. The only consistent trend seen in the field comparisons for DO was the measurements by the Orion instrument. The Orion produced the lowest readings in three of the four tests. The Orion DO probe measured 4.2 mg/L in the bench test, somewhat below the instrument average of 5.35 mg/L.

An additional indication of the difficulty of accurately measuring DO with field instrumentation is the range displayed by the bench test. The high value measured by the Solomat instrument of 8.22 mg/L was 4.75 times (475 percent) higher than the low value of 1.73 mg/L measured by the QED instrument. As shown on the plot in Appendix A-2.2, there is a nearly equal range in values above and below the mean. Two instruments are lower than the mean, and three are higher. No laboratory analysis for DO was conducted due to the inherent instability of DO and the potential for changes in the parameter over time.

4.4.2.3 Specific Conductance

No instrument displayed a consistently high or low trend in specific conductance measurements in the four field tests. The range between the highest and lowest measurements, once values stabilized during purging, varied from approximately 11 percent in Well 1786 to approximately 15 percent in Well 41691 (not including a single low value in Well 2587 during bailing). The observed range in values is appropriate given the varying conditions from test to test. Because the measurement of specific conductance is a technologically simple process of measuring electrical conductance between solid state electrodes, the relatively small range (compared to the range observed in other parameters) is not surprising.

The results of the bench test for specific conductance displayed a range of 8 percent between the highest and lowest reading (Appendix A-2.2). The highest measurement was the Orion instrument at 1,477 μS/cm, and the lowest was the Solomat instrument at 1,355 μS/cm. The average of the instruments was 1,417 μS/cm. The laboratory-measured value of an aliquot of the bench test sample water was 1,500 μS/cm. Therefore, all instruments measured values below the laboratory-verified value. The Orion (1,477 μS/cm), QED (1,460 μS/cm), and Horiba (1,450 μS/cm) were the most accurate with differences from the laboratory measurement of 1.5 percent, 2.7 percent, and 3.3 percent, respectively. The Hach at 1,360 μS/cm (9.3 percent) and Solomat at 1,335 μS/cm (11 percent) registered the largest differences from the laboratory value. The results of these comparisons should be viewed in light of the potential for differences arising from less than exact calibrations, and from the potential for changes in specific conductance of the sample water during the time between the bench test and the laboratory analysis.

4.4.2.4 Redox Potential

A broad range in field values is displayed for redox potential, much like the result of the DO measurements. However, unlike the DO measurements, the high and low values were consistently produced by the same instruments. In all the field tests the Hydrolab instrument produced the highest values, and in three of the four tests the QED instrument produced the lowest values. In the fourth test the lowest value was measured by the Orion instrument. Values measured by the Hydrolab instrument were approximately 2.5 to 3 times (250 percent to 300 percent) higher than the values measured by the QED or Orion instruments.

Results of the bench test showed the highest values were measured by the Hydrolab at 4.26 times higher (426 percent) than the lowest values, which were measured by the Orion instrument. The average value calculated for the bench test is not considered to be representative of an "expected" or "most correct" value because only the Hydrolab is above the calculated average value. The fact that the Hydrolab is notably separated from the values measured by the other instruments suggests that the Hydrolab produced erroneously high values. The other three instruments were grouped approximately evenly around a value of 100 mV while the Hydrolab reported a value of 340 mV. No laboratory analysis of redox potential was conducted due to the inherent instability of the parameter.

4.4.2.5 Turbidity

Turbidity measurement capabilities of the instruments were evaluated in the field test and in controlled laboratory conditions during a bench test, as described in the following sections.

4.4.2.5.1 Field Evaluation

Instruments were compared against one another, and against the currently used instrument (Hach DR2000) and the specialized turbidity instrument (Hach 2100P). Data collected during the field portion of the evaluation demonstrated large differences in instrument response. The data as presented in plots in Appendix A-2.1, are arranged in four ways for each of the wells tested.

1. Data from the turbidity sensors for the multiparameter instruments (in NTU units) at each well. The data are presented to assess the performance of the turbidity sensors in conjunction with flow cells (with the exception of the Horiba instrument).

2. Data from the Hach DR2000 instrument (in FTU units) for all tests at each well. These data are plotted to assess the performance of the instrument currently used in the groundwater monitoring program.

3. Data from the Hach 2100P turbidimeter (in NTU units) for all tests at each well. These data serve to assess the performance of the specialized turbidity instrument.

4. Data from the bailed test to assess the relative performance of instruments at higher turbidities. The evaluation of turbidity as a comparison between bailing and low flow pumping methods is provided in Section 5.5.

The Solomat, Hydrolab, and Horiba instruments contain turbidity sensors as part of their multiparameter capability. As the plots show in Appendix A-2.1, the Hydrolab and Horiba sensors provided comparability to the Hach DR2000 and 2100P instruments. The Solomat shows climbing values for two tests (Wells 20591 and 2587) during purging.

Values of zero turbidity in the data collected by the Hach DR2000 spectrophotometer indicate that the instrument is less sensitive to low turbidity values than the Hach 2100P turbidimeter or the turbidity sensors on the multiparameter instruments. This suggests that the Hach DR2000 may not be suitable for monitoring turbidity during low flow purging and sampling procedures, which are intended to minimize turbidity.

Data from the Hach 2100P turbidimeter indicates less variability than readings from the Hach DR2000. In addition, the instrument is more sensitive at low turbidity; when the DR2000 measured zero turbidity, the 2100P measured readings slightly above zero. This difference in response is seen by comparing readings by the two instruments in Wells 1786 and 41691.

Field data collected during purging by bailing demonstrate turbidity values greater than 1,000 NTU in three of the four wells. In the fourth well (41691), the two Hach instruments and the Horiba instrument measured different values. However, no conclusion can be drawn in a comparison of the instruments since the turbidity resulting from using bailers is sensitive to the variations in the use of the bailers (filling speed, depth of immersion, and insertion and removal technique).

4.4.2.5.2 Bench Test

The bench test to compare instrument measurements of turbidity was conducted using the 25 NTU formazin standard. The results of the test are tabulated in Appendix A-1.2 and plotted in Appendix A-2.2.

The turbidity monitoring instruments tested were the Solomat, Hydrolab, and Horiba multiparameter instruments, and the Hach DR2000 spectrophotometer and 2100P turbidimeter. The Solomat and Hydrolab multiparameter instruments employ turbidity sensors for use in flow cells, although they can be used in non-flow cell applications. The Horiba is not configured for a flow cell; the sample solution was measured in a beaker. At the suggestion of one of the instrument manufacturers (Hydrolab), the flow cells were tested in various orientations, and with and without light shielding. Hydrolab engineering personnel indicated that background light and the presence of bubbles in the flow cells have been shown to affect turbidity readings in flow cells. The impact of bubbles in the flow cells can be minimized by turning the instruments and flow cells upside down, and the impact of background light can be minimized by covering the flow cells with a material to ensure a darkened cell. The two Hach instruments employ static measurements using cuvettes in closed and darkened chambers, and as such, no modifications to the measurement technique were warranted.

The plots in Appendix A-2.2 demonstrate the results of tests against the various turbidity standards. Comparison against the 25 NTU formazin standard indicates measured values ranging from a low of 0.0 NTU for the unshielded Hydrolab sensor and in the flow cell, to a high of 32.7 NTU for the unshielded, upside down Solomat. The most accurate measurements were obtained with static (non-flow cell) measurements by the Solomat (26.2 NTU or 4.8 percent difference from standard) and the Horiba (24 NTU or 4.2 percent difference). The static measurements by the Hach 2100P and DR2000 instruments yielded values of 22.5 NTU (10 percent difference) and 31 FTU (19.4 percent difference), respectively. The most accurate measurements using the flow cells were the upside down Solomat without its wire mesh screen in the cell and without light shielding (23.8 NTU, 5 percent difference), and the upside down Hydrolab with a cloth light shielding (23.7 NTU, 5.5 percent difference).

4.5 Conclusions and Recommendations

4.5.1 Instrument Suitability

The conclusions about the suitability of the multiparameter instruments are summarized as follows:

- ***All probes are easy to use.*** Calibration and measurement were straightforward. Datalogging complexity increased with increased capabilities, but field crews were able to quickly learn instrument-specific requirements.

- ***Calibration requirements vary considerably by instrument.*** Simplest is the Horiba U-10 one-point autocalibration; calibration complexity increases up to four-point slope calibration for specific conductance with the QED Purge Saver. There was no identified relationship between calibration complexity and measurement accuracy. However, it would be expected that the three and four-point calibrations would be less subject to error.

- ***Maintenance conducted in the field test was minimal.*** Probes and sensors can be replaced in the field for the GeoTech/Orion and Solomat units. Other units allow varying degrees of field/maintenance or replacement. The Hydrolab unit probes all must be replaced by the manufacturer; DO sensor membranes are field replaceable.

- ***Multiparameter instruments are all adaptable to or include flow cells.*** The Horiba unit does not include a flow cell but one is reportedly under development. The Orion instruments are suitable for use with the GeoTech flow cell.

- ***All evaluated units included multiparameter capabilities.*** All units monitor the parameters of interest (pH, temperature, specific conductance, DO, redox potential and turbidity) except the Orion (no turbidity), Horiba (no redox potential) and QED (no turbidity) units. As a group, the individual Orion instruments operate with a multiparameter capability, though their use is more complicated by the operation of individual instruments, by the number of sensor cords, and by the need to manually install the sensors into the GeoTech flow cell prior to each use. The Hach 2100P measures only turbidity.

- ***Long-term durability was not an element of this test.*** Each instrument appears sufficiently rugged for extended field use.

- ***EPA Acceptance.*** The EPA accepts the field parameter measurement technology evaluated for all parameters measured except turbidity monitored by the multiparameter instruments. Approved turbidity measurement technology is provided only by the Hach 2100P.

4.5.2 Instrument Performance

The differences in measured values in either the field evaluation or the bench test appear to be random rather than systematic inaccuracies of individual sensors or instruments. The following conclusions about the performance of the instruments can be made.

- Within the variations expected between wells and purging/sampling events, the field evaluation demonstrated that all pH and specific conductance probes provided adequate results.

- Measurements for DO and redox potential displayed the largest range in values measured during the field evaluation, and demonstrated the difficulty in obtaining reliable field data. Despite the difficulty, multiparameter instruments in conjunction with flow cells provide the best available portable field monitoring technique for these parameters.

- The Hach DR2000 spectrophotometer currently used in the groundwater monitoring program exhibited a lack of sensitivity at values below 5 NTU. The Hach 2100P turbidimeter yielded the most consistent values and the most sensitive values at low turbidities. The Hydrolab multiparameter instrument, when covered with a light shield, produced turbidity values similar to the Hach 2100P. The Solomat multiparameter instrument produced less reliable turbidity data than the Hydrolab instrument.

- The Orion instruments are more difficult to use than the Solomat or Hydrolab units because each parameter is monitored with a separate instrument. In addition, the GeoTech flow cell requires assembly and disassembly with each sampling event to ensure adequate decontamination. The Solomat and Hydrolab units have one piece flow cells that are more easily decontaminated.

- Flow cells were demonstrated to be an acceptable method for monitoring field parameter data during purging. In concert with dedicated pump systems, the flow cells were shown to be an improvement over current RFETS procedures. With flow cells there is no sample contact with air, and no need to transfer sample to containers for parameter measurement. These factors, in addition to the real-time monitoring and digital logging of measurements, enhance the reliability and consistency of field parameter measurements.

5.0 EVALUATION OF METHODS TO REDUCE SEDIMENT IN WELLS

5.1 Introduction

Methods to lessen sediment in RFETS wells is presented in this section. Factors that contribute to excessive sediment in a well include:

- Disturbance of material by drilling activities can transport surface sediments down to lower levels within a borehole and can liberate fine-grained formation sediments from the soil matrix;
- Poorly designed screened intervals and improperly designed filter packs can allow fine-grained formation materials to enter the well;
- Well development methods may inadequately remove sediment from the well;
- Groundwater purging and sampling methods may produce turbulence which can suspend existing sediment or draw additional sediment into a well; and,
- Naturally-occurring fine-grained formation materials may continue to produce sediment even after appropriate construction and development methods are used.

The impacts of excessive sediment in the well can be significant. Potential impacts are:

- Plugging of sandpack and well screen, thereby lowering the production capacity of a well.
- Decrease in the length of standing water column due to the presence of sediment in the bottom of the well. This impact can be particularly severe in wells that have a short standing water column.
- Geochemical changes due to absorption or adsorption of dissolved chemical components to the sediment particles. This can have the effect of increasing the observed groundwater sample concentrations above representative values if excessive sediment is included in the sample.
- Geochemical changes due to introduction of uncharacterized surface or near-surface sediments into the groundwater during drilling.

5.2 Drilling Methods

Borehole drilling methods can introduce sediments into wells both through the introduction of contamination from the near-surface materials and by disruption (loosening, smearing, and segregation) of in-situ materials through mechanical drilling action.

An ideal groundwater monitoring well would be a "window" into an aquifer which does not affect subsurface conditions in any way. Unfortunately, all borehole drilling techniques impact the quality of a groundwater sample to varying degrees by introducing surface and disturbing subsurface materials. Borehole drilling is inherently intrusive, and the introduction of any mechanical equipment potentially alters the hydrogeologic conditions of the subsurface. Aseptic drilling methods have been developed to minimize subsurface disturbance.

5.2.1 Literature Review

Technical literature evaluating aseptic drilling methods or techniques is limited. Examples of aseptic drilling methods are rotary sonic, resonant sonic, and thermal. These methods can be considered aseptic because they typically result in less formation disturbance than conventional methods, use minimal or no fluid circulation, and follow the drill bit with smooth-walled flush-threaded casing of similar diameter as the bit. Advantages and limitations of these aseptic drilling methods, plus typical drilling methods used at RFETS such as hollow-stem and solid-stem augers, air and water rotary equipment, and other traditional methods are provided in Table 5-1. In addition to the drilling methods just described, certain aseptic techniques can be applied to all drilling methods to minimize cross contamination. Aseptic drilling techniques also include surface soil removal, surface casing placement, and scrupulous decontamination.

Aseptic drilling methods adequately address cross-contamination with depth, but are subject to limitations like other drilling methods. Limitations of the rotary sonic method were identified by Wright and Cunningham (1994) as the potential to add water to the formation, and to heat sample and formation materials. Ault et al. (1994) observed core growth (expansion of core due to vibration) in samples collected by rotary sonic and resonant sonic methods. In addition, the vibrations induced by these methods have the potential to drive fine-grained materials into borehole walls. Similarly, resonant sonic methods were determined by Barrow (1994) to disturb natural conditions by wedging cuttings into either the formation or sample barrel (depending on the configuration of the cutting shoe). Like the rotary sonic method, the resonant sonic method elevates core and formation temperatures, potentially affecting groundwater chemistry. Finally, thermal drilling techniques heat subsurface materials, dramatically affecting formation permeability and groundwater chemistry (Goof, 1994).

Current drilling methods used at RFETS may impact the natural geochemical condition of the subsurface. For example, contaminants were recently detected in boundary well 41691, potentially caused by surface contamination transported to depth during borehole drilling or well construction. Although not verified, this possibility suggests the need for scrupulous decontamination, borehole drilling, and well construction techniques. Typical techniques employed to mitigate the potential for downward transport of surface and near-surface soil contamination include removal of surface soil prior to drilling, and setting surface casing. Removing surface soils prior to drilling offers the advantage of removing the potential source of shallow contamination. However, surface soil removal produces investigation-derived material (IDM) which must be managed in accordance with RFETS waste disposal procedures.

FO.8 *Handling of Drilling Fluids and Cuttings* (EG&G, 1994d) describes the general procedures to be used prior to drilling boreholes. Work areas must be characterized as potentially contaminated or not potentially contaminated. In all cases, surficial soils are to be excavated to a depth of approximately 8 inches. Organic vapor and radiological monitoring are to be conducted during drilling operations. Drill cuttings must be characterized by an analytical laboratory. Positive results (above background) require appropriate recordkeeping and storage of drilling cuttings in accordance with EG&G Waste Operations requirements.

TABLE 5-1
DRILLING METHOD APPLICATIONS/ADVANTAGES AND LIMITATIONS

ASEPTIC DRILLING METHODS	
RESONANT AND ROTARY SONIC DRILLING	
Applications/Advantages	Limitations
▸ Uses high frequency mechanic oscillations to transmit resonant vibrations and rotary power through drill pipe to drill bit ▸ System collects continuous overburden and consolidated materials ▸ Exceptional drilling rates without drilling fluids or air to effectively take overburden core samples to depths of 400 feet ▸ Dual casing drill pipe used. After the core barrel has been advanced, outer drill pipe is advanced to same depth ▸ Outer drill pipe reduces sample contamination from uphole material by sealing it off prior to each core run ▸ Outer drill pipe has inside diameters of 5 and 7 inches to allow installation of well casing ▸ Outer drill pipe bits have 5 7/8 through 8 1/2-inch diameters ▸ Vibration of drill pipe during well construction vibrates and compacts coarse formation materials around well casing	▸ Must use water with bedrock coring to remove cuttings ▸ Relatively new technique with possible downtime problems ▸ Relatively expensive ▸ May require extensive repairs during drilling ▸ Does not have deep hole capabilities, generally less than 400 ft ▸ May recover more core than actual footage drilled due to expansion of core during drilling ▸ heats up core, which may impact water chemistry ▸ Displacement of material may impact physical characteristics of formation
THERMAL DRILLING	
Applications/Advantages	Limitations
▸ Uses heat to melt materials to advance drill bit and casing ▸ No cuttings are produced, minimizing waste generation	▪ Expensive new technology ▸ Heating subsurface materials likely impacts groundwater chemistry ▪ Melted formation materials could affect physical characteristics of formation

TABLE 5-1 (Cont'd)
DRILLING METHOD APPLICATIONS/ADVANTAGES AND LIMITATIONS

RFETS DRILLING METHODS	
HOLLOW-STEM AUGERS	
Applications/Advantages	Limitations
▸ Most types of soil investigations ▸ Permits good soil sampling with split-spoon or thin-wall samplers ▸ Permits water-quality sampling during drilling ▸ Monitoring well installation in most unconsolidated formations ▸ Can serve as temporary casing for coring rock ▸ Can be used in stable formations to set surface casing (example: drill 12-inch borehole; remove augers; set 8-inch casing; drill 7 1/4-inch borehole with 3 1/4-inch ID augers to rock; core rock with 3-inch tools; install 1-inch piezometer; pull augers) ▸ Relatively fast and mobile ▸ Can use continuous sampling systems in cohesive soil types	• Difficulty in preserving sample integrity in heaving formations • Formation invasion by water or drilling mud if used to control heaving • Possible cross contamination of aquifers where annular space not positively controlled by water or drilling mud or surface casing • Limited diameter of augers limits casing size. • Smearing of clays may seal off aquifer to be monitored • Penetration into hard soils to significant depths or through gravels, cobbles and boulders difficult or impossible
AIR ROTARY DRILLING	
Applications	Limitations
▸ Rapid drilling of semi-consolidated and consolidated rock ▸ Equipment and rigs generally available ▸ Allows a rough and quick identification of lithologic changes ▸ Allows identification of most water-bearing zones ▸ Allows estimate of yields in strong water-producing zones with short "down time" ▸ Borehole suitable for most types of sampling ▸ Can be used to drill inclined holes ▸ Can use downhole hammer bits to increase penetration rates	• Surface casing frequently required to protect top of hole • Drilling restricted to semi-consolidated and consolidated formations • Samples occur as small chips that are difficult to interpret • Drying effect of air may mask lower yield water producing zones, allowing only identification of significant water-bearing zones • Air stream requires contaminant filtration ▸ Air may modify chemical or biological conditions; recovery time is uncertain ▸ Requires level area for drilling since rigs are large
WATER ROTARY DRILLING	
Applications/Advantages	Limitations
• Rapid drilling of clay, silt and compacted sand and gravel • Allows split-spoon and thin-wall sampling in unconsolidated materials • Allows core sampling in consolidated rock ▸ Drilling rigs widely available ▸ Abundant and flexible range of tool sizes and depth capabilities ▸ Very sophisticated drilling and mud programs available • Geophysical borehole logging can be performed	• Difficult to remove drilling mud and wall cake from outer perimeter of filter pack during development ▸ Bentonite or other drilling fluid additives may influence quality of ground-water samples ▸ Split-spoon and thin-wall samplers are expensive and of questionable cost effectiveness at depths greater than 150 feet ▸ Difficult to identify aquifers because of use of water for drilling ▸ Drilling fluid invasion of permeable zones may compromise validity of subsequent monitoring well samples

TABLE 5-1 (Con't)
DRILLING METHOD APPLICATIONS/ADVANTAGES AND LIMITATIONS

RFETS DRILLING METHODS (Cont'd)	
HYPRO PUNCH™	
Applications/Advantages	Limitations
• Relatively rapid method of collecting groundwater sample • Can isolate zones to collect water samples from • Collects about 500 ml of water, therefore there are not large volumes of purged water to dispose of • Can collect discrete water samples at different depths from saturated formation	• Generally must be used with conventional hollow stem auger drill rig. • May be difficult to obtain water samples from silt and clay deposits because of low permeability • May be difficult to obtain water samples from aquifers that are thin, not homogeneous, and have relatively small horizontal distributions ▸ Water sample may be very turbid • Small diameter • Limited depth
OTHER DRILLING METHODS	
SOLID-STEM AUGERS	
Applications/Advantages	Limitations
▸ Shallow soils investigations • Vadose zone monitoring wells ▸ Monitoring wells in saturated, stable soils ▸ Identification of depth to bedrock ▸ Fast and mobile ▸ Undisturbed samples can be obtained by inserting sampler into open borehole once augers are removed if borehole remains open ▸ Can penetrate harder soil formations than hollow-stem	▸ Cuttings samples only unless split-spoon or thin-wall samples are taken ▸ Soil sample data limited to areas and depths where stable soils are predominant ▸ Unable to install monitoring wells in most unconsolidated aquifers because of borehole caving upon auger removal ▸ Depth capability decreases as diameter of auger increases ▸ Monitoring well diameter limited by auger diameter ▸ Unsuitable samples from weak cohesive or cohesionless granular soils, thereby limiting depth, usually near water table ▸ Obtains disturbed soil samples
CABLE TOOL DRILLING	
Applications/Advantages	Limitations
▸ Drilling in all types of geologic formations ▸ Almost any depth and diameter range ▸ Ease of monitoring well installation ▸ Ease and practicality of well development ▸ Excellent samples of coarse-grained materials ▸ Relatively economical methodology	• Drilling relatively slow ▸ Heaving of unconsolidated materials must be controlled using surface casing or fluids ▸ Equipment availability more common in central, north central and northeast sections of the United States ▸ Disturbance around bit from high energy impacts seriously effects sampler penetration rates • Rock coring and undisturbed sampling not possible • Wireline coring techniques for sampling both unconsolidated and consolidated formations often not available locally

TABLE 5-1 (Con't)
DRILLING METHOD APPLICATIONS/ADVANTAGES AND LIMITATIONS

OTHER DRILLING METHODS (Cont'd)	
LARGE DIAMETER AUGER DRILLING (Bucket or Dish Augers)	
Applications/Advantages	Limitations
► Large diameter holes (to 4 ft or larger) in cohesive soils where hole remains opens ► Relatively rapid drilling method	► Depth limited by groundwater and rock conditions ► Not suitable in cohesionless soils or soft wet clays ► Samples disturbed
AIR ROTARY WITH CASING DRIVER	
Applications/Advantages	Limitations
► Rapid drilling of unconsolidated sands, silts and clays ► Drilling in alluvial material ► Casing supports borehole thereby maintaining borehole integrity and minimizing inter-aquifer cross contamination ► No drilling muds or fluids generally required ► Efficient construction of monitoring well as casing is removed ► Minimal formation damage as casing pulled back ► Can use downhole hammer bits to increase drilling speed	► Thin, low pressure water bearing zones easily overlooked if drilling not stopped at appropriate places to observe whether or not water levels are recovering ► Samples pulverized as in all rotary drilling ► Air may modify chemical or biological conditions; recovery time is uncertain ► May not be able to drive casing through large boulders or into bedrock unless under reaming bit is used.
DUAL-WALL REVERSE AIR-CIRCULATION	
Applications/Advantages	Limitations
► Very rapid drilling through both unconsolidated and consolidated formations ■ Allows continuous sampling in all types of formations ► Minimal risk of contamination of sample ► In stable formations, wells with diameters as large as 6 inches can be installed in open hole completions	■ Limited borehole size that limits diameter of monitoring wells ► In unstable formations, well diameters are limited to approximately 4 inches ► Equipment availability currently more common in the southwest ► Air may modify chemical or biological conditions; recovery time is uncertain ► Unable to install filter pack unless completed open hole
DRIVEN WELLS	
Applications/Advantages	Limitations
► Water-level monitoring in shallow formations ► Low cost encourages multiple sampling points	► Depth limited to approximately 50 feet (except in sandy material) ► Small diameter casing ► No soil samples ■ Steel casing interferes with some chemical analysis ► Lack of stratigraphic detail creates uncertainty regarding screened zones and/or cross contamination ► Cannot penetrate dense and/or some dry materials ► No annular space for completion procedures

TABLE 5-1 (Con't)
DRILLING METHOD APPLICATIONS/ADVANTAGES AND LIMITATIONS

OTHER DRILLING METHODS (Cont'd)	
JET PERCUSSION	
Applications/Advantages	Limitations
▸ Sample collection in form of cuttings to surface ▸ Primary use in unconsolidated formations, but may be used in some softer consolidated rock	▸ Drilling mud may be needed to return cuttings to surface ▸ Hole diameter limited to 4 inches ▸ Installation slow in dense, bouldery clay/till or similar formations ▸ Disturbance of the formation possible if borehole not cased immediately
PNEUMATIC PERCUSSION DRILLING	
Application/Advantages	Limitations
▸ Percussion rock bit chips and crusher rock with hammer blows as bit rotates, chips removed by air pressure ▸ Rapid procedure for making small diameter holes in hard rock ▸ Best use is for hard massive rock	▸ Samples are only small chips, not used for sampling
CORE DRILLING	
Applications/Advantages	Limitations
▸ Continuous sampling of dense soils and bedrock units ▸ Can orient geologic features recovered with core sample ▸ Collect undisturbed samples for laboratory testing ▸ Drilling can be performed at any angle or direction ▸ Drilling can be performed with air or water ▸ Well casing, instrumentation, and testing equipment can be installed through drill casing	▸ Poor recovery in unindurated material ▸ Relatively high cost ▸ Limited borehole size, generally less than 6-inches in diameter

TABLE 5-1 (Con't)
DRILLING METHOD APPLICATIONS/ADVANTAGES AND LIMITATIONS

OTHER DRILLING METHODS (Cont'd)	
BECKER HAMMER METHOD	
Application/Advantages	Limitations
► Relatively fast drilling method ► Cutting samples are from actual depths ► Samples can be collected through drill stem using split-spoon samplers and shelby tubes ► Wells, instrumentation and testing equipment can be installed through drill casing ► Perched water is easily identified and then can be cased off as drill string advances ► Drilling penetration rates can be correlated to standard penetration rates for split-spoon sampler	► Hole size restricted from 4- to 9-inches in diameter ► Can not drill in bedrock units (metamorphic and igneous units) ► Generally limited to depths less than 300′ ft ► Limited drilling angle of 30° from vertical

Adapted from Aller et al., 1990

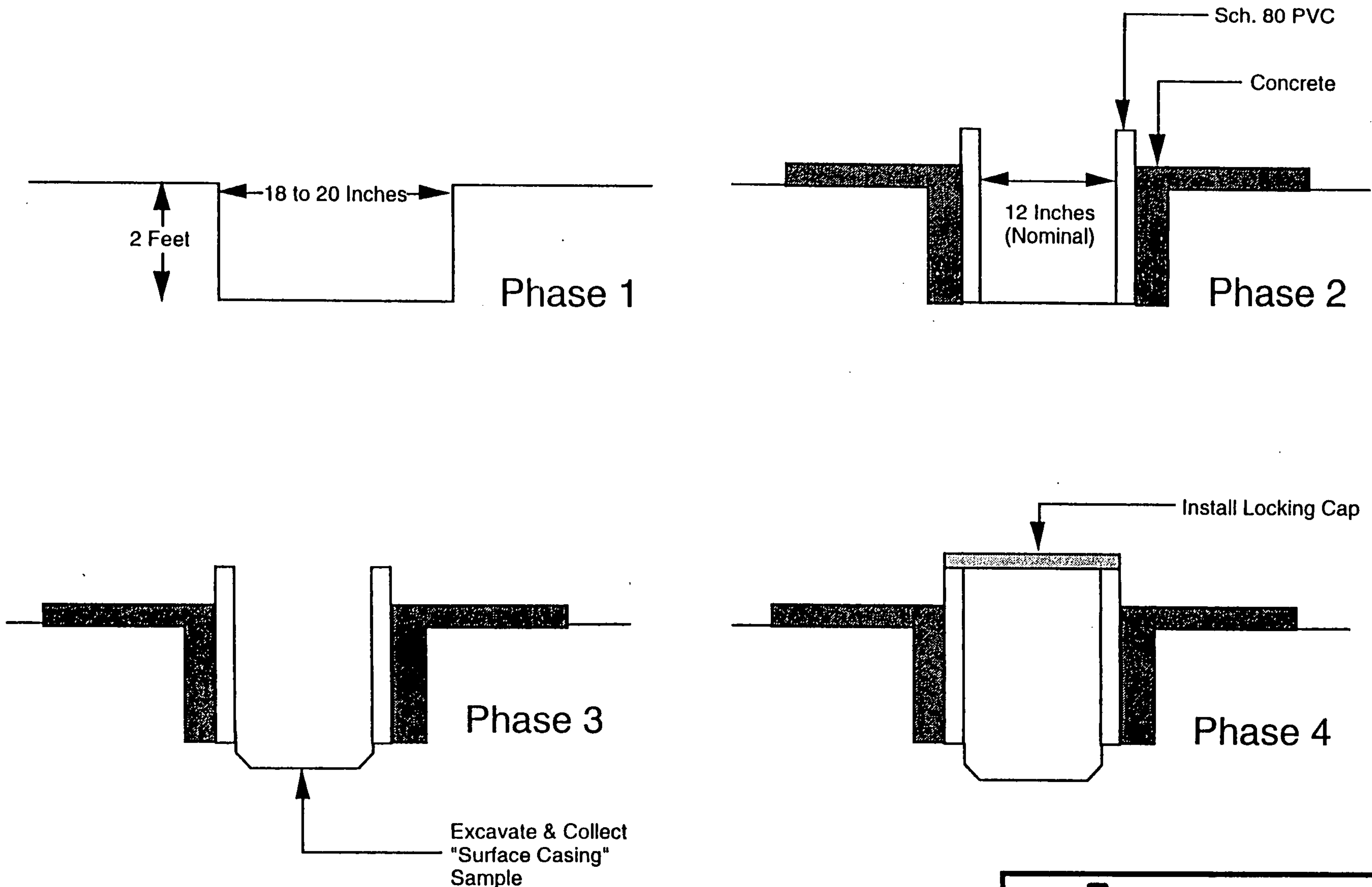
At RFETS, previous investigations have demonstrated that, where present, radionuclide contamination is limited to approximately the upper 4 inches of soil. As described above, removal of 8 inches of soil at and immediately around each proposed borehole location is required by FO.8, and is a relatively straightforward technique for minimizing the potential for surface contamination to be introduced to the borehole. Verification that the potential source of surface radionuclide contamination had been removed prior to drilling should be accomplished using readily available field instrumentation. An alternative technique recently evaluated at RFETS is described below.

5.2.2 Field Evaluation of An Aseptic Method

Surface soil contamination is widespread east of the Industrial Area of the Site as a result of wind dispersal of soil containing certain radiological constituents such as plutonium and americium. Two of the eighteen monitoring well locations (11894 and 11994) drilled by the Well Abandonment and Replacement Program (WARP) during FY94 were identified as candidates for aseptic drilling techniques as a means to assure representative sampling of soil and groundwater. The locations are east of the eastern RFETS boundary, along Walnut Creek between Indiana Street and Great Western Reservoir. The measures listed below were implemented during the drilling and sampling of Wells 11894 and 11994 to determine and/or prevent cross-contamination between potentially contaminated surface soil and the soil adjacent to the well screen.

- Prior to borehole drilling, a soil sample was collected in accordance with GT.8, *Surface Soil Sampling*, (EG&G, 1994d) and analyzed to determine the ambient constituent concentrations at each well location.

- Surface casing was installed to a depth of about 2 feet to prevent potentially contaminated surface soil from entering the borehole (Figure 5-1). The installation procedure was the same as specified in GT.3 *Isolating Bedrock from Alluvium with Grouted Surface Casing* (EG&G, 1994d), although concrete was substituted for grout to avoid the potential for frost damage. Soil from the bottom of the surface casing was collected as a discrete 2-foot sample. This sample was analyzed to determine whether the casing point was below the depth of surface contamination and to assure that no incidental material from the surface had contaminated the borehole during the casing installation activity. A locking cap was installed to prevent tampering, pending laboratory analysis of the samples. Upon confirmation that the borehole was free from contamination at the bottom of the surface casing, a drilling rig was moved



EG&G ROCKY FLATS

Rocky Flats Environmental Technology Site, Golden Colorado

CONFIGURATION OF
ASEPTIC BOREHOLE SURFACE
COMPLETION

DATE : MARCH 1995 | FIGURE : 5-1

on location. Because the soil was cobbly at the surface, a 16-inch diameter steel casing was substituted for the standard Schedule 80 PVC casing, with a corresponding increase in the initial hole size.

- All drilling activities were performed in accordance with GT.2 *Drilling and Sampling Using Hollow Stem Auger Techniques* (EG&G, 1994d). The core barrel was positioned about three inches ahead of the insert bit. The advanced core barrel position avoided the sampling of any debris carried down by the augers during drilling. All downhole drilling equipment was decontaminated prior to drilling to depth through the surface casing.

- Sample preparation and handling was also performed in accordance with GT.2. This procedure calls for sample peeling or the discarding of the portion of the core that was in direct contact with the sampler. To assure the most representative sample, only the central portion of the core was submitted to the laboratory for analysis.

- All wells were constructed in accordance with GT.6 *Monitoring Wells and Piezometer Installation* (EG&G, 1994d).

The following table presents data confirming that between one and two orders of magnitude of protection from cross contamination was achieved by the implementation of the preceding procedures.

Well Number	Analyte	Surface Soil pCi/g	Counting Error ±pCi/g	2-Foot Discrete pCi/g	Counting Error ±pCi/g
11894	plutonium-239/240	0.109	0.014	0.008	0.005
11894	americium-241	0.022	0.010	-0.001	0.005
11994	plutonium-239/240	0.252	0.024	0.010	0.005
11994	americium-241	0.063	0.024	-0.001	0.002

5.2.3 Conclusions and Recommendation

Although several aseptic drilling methods (e.g., rotary sonic, resonant sonic, thermal) are available to address specific aspects of downhole and cross-migration of contaminants, all options adversely impact subsurface conditions. The best available option to minimize such contamination includes minor modifications of existing procedures. Specifically, scrupulous decontamination of all downhole equipment, excavation of surficial soils, and isolation of surficial materials by placement of a surface casing are elements of existing procedures that address contamination issues. Disturbance of subsurface materials is likely to occur regardless of the drilling method selected. Such disturbance is best addressed by proper well design and installation, and thorough well development, as discussed in the following sections.

The following recommendation is made:

- Aseptic techniques should be used when drilling with traditional (hollow stem auger, rotary) drilling methods to minimize transport of materials from the surface or from identified zones of subsurface contamination into a well's screened interval.

5.3 Well Design and Installation

5.3.1 Literature Review

Well materials and methods used during their placement in the borehole can affect the volume of sediment present in the well. Properly sized filter packs and well screens are necessary to reduce the volume of sediment which can enter the well.

Well screens should be surrounded by a filter pack that has a uniform grain size, is more coarse, and has a higher permeability than the natural formation material. The physical characteristics of the natural formation material dictate the grain size of the filter media and the well screen slot size. According to EPA's *Handbook of Suggested Practices for the Design and Installation of Groundwater Monitoring Wells* (Aller et al., 1990), formation material grain size is best determined by sieve analysis. Filter pack grain size should be determined based on either the average formation material grain size (50 percent retained) or the 70 percent retained size. Some researchers suggest that if the average grain size method is used, the filter media should be 3 to 5 times the 50 percent retained size, or more conservatively, 2 times the average size. The EPA *RCRA Ground-Water*

Monitoring: Draft Technical Guidance (DTG) recommends a filter media size 4 times the 70 percent retained size for uniform fine-grained formation materials (EPA, 1992b). For coarse, non-uniform materials, the filter pack size should be up to 6 times the 70 percent natural material grain size.

The well screen slot size should be selected only after the filter pack grain size is specified. The screen slot size is generally chosen based on its ability to retain 85 percent to 100 percent of the filter media. The actual configuration of the well screen is commonly cited as a significant factor affecting the introduction of sediment into the well (Driscoll, 1986). Well screen slots are commonly either machine-cut or continuous slot wire-wrapped. Machine-cut slots are typically inexpensive but inefficient: open area for 0.010-inch slots in a 2-inch Schedule 40 screen is typically less than 3 percent (Driscoll, 1986). Slot openings are parallel in cross section, and irregularly-shaped particles are likely to become wedged within the slot, decreasing efficiency. Continuous slot wire-wrapped screen is more expensive but more efficient. Depending on the width of the wire, open area ranges from about 4 percent to about 17 percent (Driscoll, 1986). Continuous wire-wrapped screen is also less susceptible to plugging: the wire is triangular in shape, and welded in position so the slot widens going into the well. Irregularly-shaped particles are less likely to wedge within the slot.

An additional type of well screen is the pre-packed double screened configuration. This screen type consists of an outer screen and an inner screen with the annular volume filled with filter media. The screen slot and sand sizes are matched to one another. This screen type simplifies installation because: no sandpack to pour and monitor; no concern over controlling placement; a finer- grained sandpack (to 30-70 mesh) can be installed without the risk of floating (not settling) in muddy borehole water; and, if a sufficiently large borehole is drilled, a second, more coarse sandpack can be poured around the outside of the screen assembly. The drawbacks to the use of pre-packed well screens are: they are relatively expensive (4 to 8 times the cost of conventional screens) and they are available in a limited range of slot and sand sizes (potentially minimizing the suitability of prepacked screens over a wide range of conditions, including the fine-grained materials that predominate at RFETS).

Filter media should be chemically inert; the best materials are industrial grade quartz sand or beads. Other filter pack materials should be analyzed for cation exchange capacity and organic compound content. The DTG cites the grain size selection process recommended by Aller et al. (1990), and adds that a 1- to 2-foot layer of fine sand should be placed over the filter pack to prevent the intrusion of the bentonite seal into the filter pack (EPA, 1992b).

Boyle (1992) suggests the use of air injection for placement of filter pack and well sealant materials, instead of tremie pipe or gravity placement. A dry injection system is used to ensure positive placement, and to minimize the potential for bridging. The system may be used with any drilling equipment, but requires the use of a patented injector system consisting of an air tank and supplementary equipment.

5.3.2 Current Practice at RFETS

Well construction has typically used standard industry practice for construction of wells installed in fine-grained materials (see Table 1-1). Given the fine-grained materials that predominate at RFETS, a large percentage of wells yield high turbidity values. In addition, the radiological contamination in the surface soils has potentially been transported down into the screened intervals in some wells. At locations where bedrock completions have been located below alluvial contaminant plumes, alluvial contamination has potentially been brought into the deeper screened intervals.

A study conducted at RFETS in 1990 evaluated well design in light of the predominant fine-grained materials at the site (Shear, 1990). The salient aspects of that study are summarized below.

- Accepted well design procedures use the 20 percent passing (80 percent retained) grain size of the finest naturally occurring unit as the starting point in filter pack selection. A factor ranging from 4 to 9 is multiplied by that grain size to determine the 30 percent passing grain size for the filter material. The multiplying factor depends on the uniformity of the aquifer material. A uniformly graded filter material is recommended. A correctly sized filter allows only those materials smaller than the 10 percent fraction of the filter to pass through the screen slots. Hence, the slot size is selected using the 90 percent retained filter pack grain size criteria.

- Once the filter pack and its respective slot size are chosen, well development is essential to reestablish the natural permeability of the formation and remove excess fines in the natural material nearest the borehole.

- The subsurface materials at RFETS are very fine-grained; often 50 percent of the material is silt- and clay-sized fractions. Traditional well design criteria would call for an unreasonably fine-grained filter pack and unrealistically small slot sizes, as small as 0.004 inches. Such small screen slot sizes would further reduce already low well yields.

- The current design allows particles finer than a slot size of 0.010 inches to enter the well, which results in sediment accumulation and subsequent turbidity. Since the smallest commercially available slot size is 0.006 to 0.008 inches, the only other alternative is to use a finer-grained filter pack. However, the filter material is limited by the slot size; anything finer can enter the well during development. A finer (20-60) filter pack can be used (as a special order). While a slight reduction in turbidity may result, the cost-effectiveness and the logistical difficulty of special orders should be carefully scrutinized. For example, use of 20-60 filter would only prohibit those particles smaller than the #40 sieve size from entering the well. Particles finer than 0.010 inch will continue to flow into the well.

- Many of the monitoring wells exhibit very low recovery rates and have characteristically low static water levels. These two factors contribute to extensive times required for well development. Even in these conditions, continued long-term development can eventually remove the excess fines adjacent to the borehole. Monitoring wells will continue to yield turbid samples, due simply to the extremely fine-grained natural materials in which they are completed.

5.3.3 Field Evaluation of Well Construction Methods

Alternative well construction methods were evaluated for their potential to decrease sediment in monitoring wells at RFETS. The evaluation specifically compared alternative construction methods to standard RFETS methods. The evaluation involved three wells installed within approximately fifteen feet of one another in the Rocky Flats Alluvium. Two of the wells (ID numbers 11694 and 11794) were newly installed and were compared with existing well B200789. The wells were installed using similar drilling and installation techniques, and to the extent possible, had comparable total depths and screened intervals. Borehole logs and well construction details are presented in Appendix G-1. The methods compared involved wells with the following constructions:

Well B200789:	Standard RFETS construction consisting of 4.5-inch diameter stainless steel wire-wrapped screen having 0.010-inch slots, and a 16-40 mesh sandpack;
Well 11694:	Two-inch diameter polyvinyl chloride (PVC) wire-wrapped screen having 0.008-inch slot, and a 16-40 mesh sandpack, and;
Well 11794:	Two-inch inside diameter PVC wire-wrapped dual screen with prepacked annulus between the screens. The screens have 0.006-inch slots, and the prepack has a 30-70 mesh gradation. The annular space between the outer screen and the borehole wall was sandpacked with a 16-40 mesh sand.

The intent of the evaluation was to conduct a preliminary assessment to determine: (1) if a finer screen slot size is effective in lowering sediment in RFETS wells, and (2) if the alternative technology of pre-packed dual screens having smaller slots and finer sandpack is warranted for detailed study for use at RFETS. The well screen and sandpack constructions chosen were based on alternatives suggested in Shear (1990). The Shear report is presented in its entirety in Appendix G-2.

The evaluation was completed by comparing the results from laboratory Total Suspended Solids (TSS) analyses run on samples collected from each of the wells. The wells were sampled by bailing and by pumping at three different flow rates. Pumping flow rates were chosen to provide a range of discharges from relatively low turbulence conditions to high turbulence conditions at near maximum drawdowns. All three wells were subjected to the same range in pumping rates. The well discharge rate using the bailer method is approximately equivalent to pumping at the medium pumping rate (Test#2, 1.0 to 1.1 gpm). Bailed samples were collected using RFETS standard operating procedures (SOP GW.6). Field-measured turbidity was used as an additional method to observe differences in the sediment content in well discharge water owing to different configurations of well screens and sandpacks. Turbidity readings were observed during the duration of pumping at each flow rate until the readings became relatively stable. Samples were then collected for laboratory TSS analysis. Table 5-2 presents the results of the TSS analyses and turbidity field measurements.

TABLE 5-2

RESULTS OF TOTAL SUSPENDED SOLIDS (TSS) ANALYSES AND TURBIDITY MEASUREMENTS FOR THREE WELL SCREEN AND SANDPACK CONFIGURATIONS

Well ID	Screen Slot Size (inches)	Sandpack Gradation (mesh No.)	Test #1 Pumped Slow 0.5-0.7 gpm		Test #2 Pumped Medium 1.0-1.1 gpm		Test #3 Pumped Fast 1.1-1.6 gpm		Test #4 Bailed	
			TSS Conc. (mg/l)	Turbidity (NTU)	TSS Conc. (mg/l)	Turbidity (NTU)	TSS Conc. (mg/l)	Turbidity (NTU)	TSS Conc. (mg/l)	Turbidity (NTU)
B200789	0.010	16 - 40	<4	5.7	<4	5.0	6	8.8	164	O.R.
11694	0.008	16 - 40	4.6	12.5	<4	5.3	<4	5.4	6296	O.R.
11794	0.006	30 - 70	6.8	5.4	4.4	6.4	14.4	23.6	2236	O.R.

Notes:
1. Pumped Slow, Medium, and Fast are relative pumping rates and provided for the purposes of clarity and comparison only.
2. Reported are tubidity readings at the ending of purging and just prior to sample collection. Turbidity measured with Hach DR2100 instrument.
3. Well No. 11794 dewatered rapidly at the fast pumping rate (during Test #3).
4. O.R. indicates that turbidity instrument readings were over range.

As shown on Table 5-2, the TSS analyses indicate that the prepacked dual-screen construction produced higher suspended sediment concentrations during pumping than the either of the single-screen constructions. Suspended sediment concentrations obtained in samples collected with bailers were highest for the 0.008-inch slot single-screen and lowest for the 0.010-inch slot single-screen construction (standard RFETS construction method). Field measured turbidity values were not as sensitive as TSS concentrations. No obvious trend in the turbidity data is apparent.

Based on the results of this preliminary evaluation, it can be concluded that neither of the alternative construction methods are superior to the standard RFETS method. No change in well screen type, slot size, or sandpack gradation is warranted for future well installations at RFETS. The evaluation must be considered preliminary because of factors that introduce uncertainty in the data collected. The evaluation was conducted at one location at RFETS and did not consider the range of subsurface conditions that exist at RFETS. In addition, the existing well has been purged and sampled since 1989 and has likely undergone significantly greater development than the two new wells. Finally, though the wells are located within approximately 15 feet of one another, the borehole logs indicate that the Rocky Flats Alluvium within the screened intervals varied from predominantly silty sands to predominantly well graded gravels.

5.3.4 Conclusions and Recommendations

Though the occurrence of sediment in RFETS wells may be mitigated through the use of optimized well screen and filterpack design, the results of the field evaluation comparing two alternative designs to the standard RFETS design indicates that current well construction methods are adequate. It is recommended however that additional data be collected as part of standard well installation procedure. Specifically, it is recommended that grain-size data be obtained using field sieves during drilling within a subsurface interval intended for screening. Though custom filterpacks and well screens for all formation grain-size possibilities are impractical, further study of the data that would be collected could help identify practical adjustments to the existing design or confirm the existing well design as the optimal "average". A limited number of designs could be identified, from which could be chosen an optimal design based on the formation to be screened or the intended location for a well on site. In that way, a specific design for each well would be chosen prior to a field program.

5.4 Well Development Methods

As previously discussed, all drilling techniques impact subsurface geologic conditions and, hence, to some extent, hydrogeologic conditions adjacent to the wellbore. Drilling methods smear clayey or silty formations along borehole walls to varying degrees, decreasing permeability. Percussion and vibratory methods can segregate unconsolidated materials causing coarse materials to migrate to the borehole wall, thereby producing potential flow pathways around well bore seals.

Rotary drilling methods use a variety of fluids to transport cuttings to the surface. The use of air as a transport medium may cause volatilization of organic compounds or oxidation of metals. Water as the transport medium will likely dilute formation water and/or enhance formation of a "cake" of smeared materials along the borehole wall. That is, the addition of drilling muds may affect both permeability and subsurface geochemistry.

Each of these impacts may be addressed to some degree by well development, which is intended to return the subsurface to pre-drilling conditions by flushing formation water through the borehole at flow rates faster than natural groundwater flow. A literature review of well development techniques is provided in the following section.

5.4.1 Literature Review

According to Aller et al. (1990), three factors affect monitoring well development:

- Type of geologic material;
- Type of drilling technology employed; and,
- Design and completion of the well.

Unconsolidated deposits often display a stratigraphic heterogeneity as a result of well development. Highly permeable zones within one well are likely to be more developed than less permeable zones. Samples collected from a well completed in stratified materials will be more representative of the permeable portions of the aquifer.

Each drilling method specifically impacts the natural conditions of the geologic formation, such as smearing clays along the borehole walls, near-hole material segregation, or forcing air or water into the formation. Each type of impact should be addressed in the development program. For example, a development program for wells drilled with water rotary techniques would be directed towards removal of injected water. For wells drilled with air rotary, a development program directed towards flushing fines from the borehole walls would be appropriate.

Furthermore, it is not possible to construct a sufficiently fine-grained filter pack that will prevent the entry of clay or silt formation materials into the well. Every time groundwater in the well is agitated, the fine particles are mobilized and become part or all of the turbidity that potentially compromises the representativeness of the groundwater sample. Currently there is no effective solution to this problem since constructing wells with extremely fine-grained filter pack materials is likely to result in the filter becoming clogged with clays during development or sampling. Furthermore, there is a practical limit in the minimum grain size when placing filterpack into muddy borehole water.

Aller et al. (1990) provides the following comments about well development.

- Developing the formation at the interface between the outer perimeter of the filter pack and the inner perimeter of the borehole is extremely difficult. Any mudcake or natural clay deposited on this interface is very difficult to remove; incomplete removal can have unquantifiable short- and long-range impacts on the quality of sampled groundwater.

- This difficulty is multiplied when attempting to develop a representative well in an aquifer which is stratified, particularly where there is substantial variation in lithology between the stratified zones.

- Collecting a non-turbid sample may not be possible in all cases because there are some monitoring wells that cannot be sufficiently developed by any available technique. This may be the consequence of the existence of turbid water in the formation or the inability to design and construct a well that will yield water in satisfactory quantity without exceeding acceptable flow velocities in the natural formation.

- Adding clean water of known quality must be done only as a last resort, and every attempt must be made to re-establish natural conditions.

Bailing is identified by Aller et al. (1990) as an effective development technique in relatively clean, permeable formations. The high-energy action of a free falling bailer into a well mobilizes fines, allowing efficient development. Using a surge block reverses groundwater flow, creating an inward and outward flushing action. Pumping, overpumping, and backwashing also mobilize particulate material. Using pumps without reverse-flow check valves allows water to flow back into the well during shutoff cycles, creating reverse flow conditions similar to those provided by bailing and surging. Where monitoring wells are installed in formations that have low hydraulic conductivity, none of the preceding well development methods have been found to be completely satisfactory.

The process of development induces a flow of groundwater into the well; the flow is often in one direction, which can lead to bridging of fine particles. Flow reversal should be induced to break down the bridging. Overall, the most effective and efficient method available for inducing flow reversal during well development is the careful use of a properly constructed surge block. According to the DTG, the well development methods that will generally be approved by the EPA include bailing, surging with a surge block, pumping, overpumping, or combinations of these methods (EPA, 1992b). Development methods that involve adding water or air (air-lifting of water) to the well are rarely permissible.

Julian and Young (undated) utilized downhole flow meters to study the effects of various well construction and development methods on flow distributions and drawdown responses. Boreholes were drilled with hollow-stem augers and drive and wash methods, and wells were constructed with natural backfill or gravel wash. Well development methods included overpumping, backwashing, and mechanical surging. The tests were conducted in stages, with each development method applied to each well. Results varied widely according to the hydrogeologic conditions at each well, but in all cases the results indicated that well development reduced the positive skin effects (mudcake) on the borehole wall and enhanced well yield. No well development method was identified as superior to others.

Development can be considered complete when turbidity samples collected periodically during well development yield results with turbidity values less than 5 NTU. If that value cannot be attained, the EPA considers the well to be improperly constructed unless it can be demonstrated that the turbidity is an artifact of the surrounding geologic materials rather than of improper construction materials or technique (EPA, 1992b).

Recent EPA Region VIII SOP guidance recommends well development methods such as surging, bailing, or pumping and backwashing to encourage flow through the well screen, followed by removal of fine sediments from the well casing. Pumping rates during development should exceed purging and sampling pumping rates, and the natural groundwater flow velocity (EPA, 1994a).

No well development procedure adequately addresses low yield formations. According to Aller et al. (1990), "it is not possible to design a sufficiently fine-grained filter pack that will prevent the intrusion of clays". When the well is sampled, the fine-grained materials will be mobilized and turbid samples will result. Using extremely fine-grained filter media solves the problem only temporarily, as it ultimately can become clogged by the mobilized formation fines (Aller et al., 1990).

EPA Region VIII SOPs also identify development of low yield wells as problematic (EPA, 1994a). Water may be added to the borehole before well construction, or to the well during development, to flush out fines, but only as a last resort and after acceptance by the EPA. Periodic standard development, with recovery intervals, may be the best option. The Shear (1990) study concluded that wells completed in the fine-grained materials at RFETS may require up to several years to develop, due to the inadequacy of current materials in preventing fines from entering wells.

5.4.2 Current Practice at RFETS

Current well development procedures utilized at RFETS are outlined in GW.2 *Well Development* (EG&G, 1994d). The procedures require the use of low energy methods, such as inertial pumps or bottom discharge/filling bailers, when developing new wells. High energy methods are not to be used due to the possibility of formation fines clogging the well screen. Formation water and fines are evacuated by slowly lowering and raising the inertial pump or bailer intake throughout the water column.

Generally, a minimum of five well casing volumes of water are removed from a well. Special procedures are to be followed for unusual circumstances. If the borehole was drilled with water as the drilling fluid, an additional volume totalling the net amount added to the formation must be removed. If the well is dry or dewaters during development, the well will be considered undeveloped and adequate for water level measurements only, or additional water may be added to the borehole to mobilize fines.

Re-development of existing wells should follow the same procedure as that used for developing new wells. However, the primary objective during re-development is to remove sediment from the well. Secondary objectives are to stabilize field parameters and remove five well casing volumes to ensure that formation water will be collected when sampling begins.

5.4.3 Conclusions and Recommendations

Well development can be problematic at RFETS. Limited saturated thickness, relatively low hydraulic conductivities, and the consequent slow recovery rates have resulted in the evolution of procedures requiring low energy development techniques. Yet to effectively remove sediments loosened or smeared during drilling, vigorous and turbulent methods are often required. One cause for the plugging of sandpack and well screens during vigorous development at any site is the lack of properly designed wells. Another cause is the fine-grained nature of much of the subsurface materials at sites such as RFETS. Because of the presence of considerable fine-grained materials, it is likely that even with strict well design and adequate development techniques, many wells would decrease in production capacity over time or would continue to produce sediment. Consequently, the following recommendations consider both the potentially unavoidable presence of sediments in RFETS wells, and the methods of drilling, well installation, development, and sample collection which when applied together serve to mitigate the impacts to natural groundwater quality of less than fully developed wells. Following are recommended approaches.

- Continue to use low energy development procedures that minimize turbulence at well locations having typical sediment volumes. At locations with more severe sediment conditions or where well production capacity is adequate, high energy development procedures such as bailing sediment out of a borehole prior to well string installation, use of a surge block, or flushing with external water may be desirable.

- Utilize low flow rate purging and sampling techniques (discussed in the next section) to minimize the entrance velocities of water entering a well. Low entrance velocities minimize the re-suspension of sediment and maintain low turbidity. Therefore, cross contamination is minimized because the small amount of sediment produced by low flow rate purging and sampling is more likely to be representative of the screened zone of that well.

5.5 Groundwater Purging and Sampling

Monitoring well purging and sampling techniques have evolved in recent years as investigators have refined methods to collect samples representative of formation water. Hydrogeologists have long recognized that groundwater standing in a monitoring well may not be chemically representative of formation water, due to sample contact with air or to changes in the energy state (induced flow or turbulence) of the sample. Accordingly, standard groundwater monitoring well sample collection protocol has usually required the "purging" of standing water from a well prior to sample collection. EPA guidance suggests that a minimum of three well volumes of water be removed from the well before sampling (EPA, 1986a). Certain indicators of water quality, such as pH, temperature, and specific conductance, are monitored during the purging process. When these parameters stabilize (defined by SOP GW.6 as +/- 10 percent of the previous measurement), water within the well is generally assumed to be representative of formation water.

However, there are limitations associated with this standard method. First, the method does not adequately address slow recharge wells. Purging activities may dewater the well prior to stabilization of parameters. The sample must be collected after waiting for the well to recharge, and exposure to air during recharge could alter the chemical composition of the water. Second, the purging method itself could alter chemical composition. Traditional purging activities utilize bailers or pumps to evacuate water; field crews often purge wells as quickly as possible to maximize efficiency, and bailers or pumps operated at maximum speed are likely to introduce air into the water or disturb sediments in the well. The introduction of air may cause degassing of volatile organic compounds or oxidation of certain inorganics. The suspension of sediments may cause chemical constituents sorbed to soil particles to be collected with the groundwater. These constituents may then be detected during subsequent laboratory chemical analysis, indicating higher concentrations than are actually present as constituents of the groundwater. Third, suspended particles have typically been removed from samples by filtration with a 0.45-micron filter. Filtration has recently been identified as inadequate from both technical and regulatory bases (EPA, 1994a). Objections include concern over filtration not capturing particles less than 0.45 microns, the potential for degassing the sample during the filtration process, the potential for introducing contaminants from the filter medium, and the potential for filtration to remove colloidal particles (typically between 0.1 and 10 microns in diameter) which in fact occur as natural groundwater constituents. Finally, the purging process often generates significant volumes of water. Purged water, and water used for decontamination purposes, must be disposed of properly. RFETS handling and disposal of the water is costly and logistically difficult.

The groundwater industry has recently attempted to develop alternative technologies and methods to address the problems described above. Low flow sampling (also called Micropurging, a registered name by QED Environmental Systems, Inc. [QED]) is a technique whereby discharge rates during groundwater purging and sampling approximate natural well recharge rates. The technique is based on the premise that flow-through groundwater contained within the screened interval of a well is representative of the groundwater in the adjacent formation. Stagnant water may be present in the unscreened portion of the water column above the screened interval or in the well sump below the screen, but by utilizing dedicated sample devices and low flow rates for purging and sampling, mixing stagnant and fresh water is avoided.

Low flow sampling techniques have the benefits of not dewatering wells (except those completed in very low permeability formations), minimizing degassing and oxidizing of groundwater constituents, and minimizing turbidity normally generated by pumping or bailing. Additionally, it is not necessary to purge the traditional volumes of water required for complete removal of stagnant water.

Possible objections to low flow sampling are based on the concern that samples collected by low flow sampling techniques may not duplicate samples collected by traditional methods. Numerous studies have been conducted to investigate the viability of the low flow sampling concept. A summary of technical literature describing studies, regulatory agency guidance, and investigations of low flow sampling is presented in the following section. Discussions of the current groundwater purging and sampling procedures used at RFETS are presented in subsequent sections, with a field evaluation to test the feasibility of the method at RFETS.

5.5.1 Literature Review

Technical literature devoted to the investigation of low flow sampling techniques typically focuses on one or more of the following factors:

- Purge flow rate;
- Water level drawdown;
- Field parameter stabilization;
- Filtered vs. unfiltered samples;
- Laboratory parameter stabilization;
- Purge volume and pumping duration;

- Equipment type;
- Dedicated vs. portable systems;
- Pump intake location; and,
- Cost.

Technical literature pertaining to these factors is summarized in the following sections.

5.5.1.1 Purge Flow Rate

Industry practice has traditionally utilized low flow rates, such as 1 liter per minute (L/min) or less, when collecting groundwater samples. Recent studies suggest that low flow rates should also be utilized when purging prior to sampling. A study conducted by the Robert S. Kerr Environmental Research Laboratory (RSKERL) recommends the use of low flow rates during both purging and sampling (EPA, 1992a). The Environmental Protection Agency (EPA), in its Draft Technical Guidance (DTG) document (EPA, 1992b), states that purging is best accomplished by removing water from a well at low flow rates using a pump. Puls (1994a) clarifies that low flow refers to flow velocity at the well screen, not the pump discharge velocity. Flow rate should match the natural groundwater flow velocity, should be at rates below those used to develop the well, and should be at or below a well's recovery rate (Puls, 1994b). The DTG states that the rate at which groundwater is removed from the well should ideally be less than 0.2 to 0.3 L/min (EPA, 1992b). Wells should be purged at or below their recovery rate so that migration of water in the formation from above the well screen does not occur (EPA, 1992b). A low purge rate will also reduce the possibility of stripping VOCs from the water, and will reduce the likelihood of mobilizing colloids or clay-sized particles that are immobile under natural flow conditions (EPA, 1992b). However, if a bladder pump has been chosen as the sampling device, it must be operated at 0.1 L/min or less when collecting samples for VOCs (EPA, 1991).

It should be noted that low flow sampling will not minimize natural turbidity. Natural turbidity may exist where conditions are favorable for the existence of stable suspensions (e.g., low ionic strength waters, geochemical supersaturation, high clay content). However, excessively rapid pumping for the local hydrogeologic conditions is a frequent cause of artificial turbidity (Puls et al., 1992).

Kearl et al. (1992) used a colloidal borescope to assess the effects of purging, sampling, and filtering from a hydrodynamic (i.e., transient pumping conditions) standpoint. The study concluded that samples should be collected at flow rates of 0.1 L/min. Pumping at that rate shows no increase in colloidal density.

5.5.1.2 Water Level Drawdown

Water level drawdown monitoring is a common method to determine if the pumping flow rate exceeds groundwater flow velocity. Depression of the water table indicates exceedance of well capacity, a potential for excessive well inflow velocities, and a potential for the mixing of stagnant and fresh water. According to Robin and Gillham (1987), a relatively sharp interface appears to be maintained between the water in the screened interval and the water above the screen. The presence of the interface suggests that it is possible that purging at or near a well's natural flow-through conditions could maintain the chemical integrity of the water within the screened interval. Kearl's borescope study of horizontal laminar flow observed in the well screen indicates that stagnant water in the well casing does not mix with water in the well screen as long as water level depression is minimized (Kearl et al., 1992).

The RSKERL study also recommends a minimal disturbance of the stagnant water column above the screened interval (EPA, 1992a). Recommendations from a study at a Fernald, Ohio site concluded that samplers should avoid disturbance of the water column and determine a purge rate that will maintain a constant water level (Fernald Environmental Restoration Management Corporation [FERMC], 1993). Bangsund et al. (1994) recommended a target drawdown of 0.5 feet of less.

In low permeability formations, drawdown may be unavoidable. The DTG recommends that if a well is purged to dryness or full recovery exceeds two hours after purging, the well should be sampled as soon as sufficient groundwater has entered the well to enable collection of necessary groundwater samples (EPA, 1992b). Even if the well has been dewatered during purging, sampling should be done at the lowest practical flow rate in order to minimize turbulence.

5.5.1.3 Field Parameter Stabilization

Most researchers relied on stabilization of field parameters during purging to identify when representative formation water was attained. Puls (1994b) states that low flow sampling uses parameter stabilization criteria to determine when purging is completed and recommends monitoring field water quality parameters during purging. Further, the DTG recommends that purging continue until measurements of turbidity, redox potential, and DO have stabilized within approximately 10 percent over at least two measurements (EPA, 1992b).

However, the Fernald study concluded that field parameter stabilization is not required to determine when to collect representative samples. Field parameters should be monitored only to determine and confirm baseline site conditions (FERMC, 1993).

Puls et al. (1992) monitored the following water quality indicators during well purging: DO, pH, Eh, temperature, specific conductance, and turbidity. Sampling was not conducted until all indicators had reached steady state (two to three casing volumes). In all cases turbidity was slowest to reach steady state values, followed by DO and redox potential. Temperature, specific conductance, and pH results were generally insensitive during well purging.

Barcelona et al. (1994) found that it was rarely necessary to purge more than two bore volumes to achieve parameter stabilization, with an average purge amount of one half bore volume.

5.5.1.4 Filtered vs. Unfiltered Samples

Many studies have focused on the goal of eliminating field filtration of samples intended for metals analysis. Research has shown that the method by which the samples are collected has a greater impact on sample quality, accuracy, and reproducibility than whether the samples were filtered or not (EPA, 1992a). When pumping rates greatly exceed formation groundwater flow velocities, large differences between filtered and unfiltered samples are observed, and neither are representative of values obtained with the low flow rate samples (Puls et al., 1992). There is a strong inverse relationship between turbidity and representativeness of samples. Sample collection procedures which induce artificially high levels of turbidity have the greatest negative impact on sample quality with respect to metals analyses (EPA, 1992a).

All research concluded that unfiltered samples collected via low flow methods are equivalent to filtered samples collected via traditional methods (e.g., Clark et al., 1992; Bangsund et al., 1994; Greacen and Silvia, 1994). Collection of unfiltered samples for metals analysis was recommended (EPA, 1992a; Kearl et al., 1992; Kearl et al., 1993). However, as Puls et al. (1992) pointed out, if one objective is accurate determination of dissolved inorganic concentrations, then samples should be filtered through 0.1-micron pore size filters or smaller in the field using in-line devices. The use of 0.45-micron filters could result in the inclusion of colloidal materials less than 0.45 microns, which will result in incorrect concentrations of dissolved inorganic constituents.

5.5.1.5 Laboratory Parameter Stabilization

Few studies have researched stabilization of laboratory parameters during purging. Barcelona et al. (1994) found that VOCs stabilized during purging within an average of one half well bore volume, at values 15 to 23 percent higher than prepurged concentrations. At the Fernald site study, samples were collected after twice the pump and tubing volume was purged, after one well volume was purged, and after three well volumes were purged. The samples were analyzed for metals and inorganics. No statistical difference between the sample results was seen (FERMC, 1993).

A 1988 study of VOC concentrations in slowly recharging wells used bailers to collect samples before and, at various time intervals, after purging. The wells were completed in materials with hydraulic conductivities ranging from 1×10^{-6} to 7×10^{-5} cm/sec (Herzog et al., 1988). Statistical evaluations of analytical results identified no significant differences (at the 95 percent confidence level) between VOC concentrations in the post-purge samples, collected at 2-, 4-, 6-, 24-, and 48-hour intervals.

5.5.1.6 Purge Volume and Duration of Pumping

The presence of representative water within the screened interval presents the possibility of collecting a sample without (or with very little) purging (Robin and Gillham, 1987). However, Barcelona et al. (1994) noted a marked difference between prepurged and purged indicator parameters, indicating the need to purge wells prior to sampling.

Purge volumes and/or pumping durations reported by researchers using the low flow sampling method varied considerably. At the upper range, Bangsund et al. (1994) found that field parameter monitoring indicated that water quality stabilization was reached after 0.66 to 3 well volumes. Time to attain stabilization ranged from 70 to 120 minutes. Puls et al. (1992) found that the purge time for water quality parameter equilibration using a peristaltic pump was 1.3 hours, or about two casing volumes.

However, recent Puls research (1994b) concluded that a direct relationship is often evident between the flow rate used and the purge volume required. Kearl stated that, based on the colloidal borescope study, wells should not be purged at all (Kearl et al., 1992). Another Kearl study (et al., 1993) determined that only the <u>sample pump and tubing</u> should be purged approximately 2 volumes; it is not necessary to purge the entire casing volume.

The most important factors affecting purge volume appear to be hydraulic and geologic heterogeneity, water chemistry, well construction, pumping rate, pump size, and portable versus dedicated systems (Puls, 1994a). Purging is not recommended in some situations. For example, purging may not be applicable when volatile organics are monitored in fine-grained sediments. The sediments can strip the VOCs from well water. Purging of slow recovery wells introduces air into the formation as the well dewaters. Studies have shown that up to 70 percent of the VOCs in water can be lost once air enters the formation (Puls, 1994b).

5.5.1.7 Equipment Type

Considerable research has been conducted on the impacts various sampling devices may have on chemical constituents and indicator parameters in groundwater. Gass et al. (1991) tested an electric submersible pump in controlled (laboratory) conditions and found no impacts to organic or inorganic compounds when samples were collected at low flow rates (0.1 L/min). It should be noted that, prior to sample collection, purge rates in excess of 30 liters per minute were used.

Puls et al. (1992) compared low speed and high speed submersible pumps, bladder pumps, peristaltic pumps, and bailers. Results of the study indicated that the amount of particles re-suspended by a low speed submersible pump was 13 times greater than by a bladder pump. Additionally, the amount of particles suspended by a high speed submersible pump was over 20 times greater than by a bladder pump. Bailed samples were collected after a standard three casing volumes had been purged. Bailed sample concentrations for chromium were two to three times higher than values from samples collected by a peristaltic pump. Sampling with the peristaltic pump consistently produced the most reproducible results and provided increased confidence that these samples were more representative than those collected with the bailer. Equilibrated turbidity values with the peristaltic pump were generally less than 2 NTU, while with the bailer they were greater than 200 NTU.

At another site, peristaltic turbidity values were less than 5 NTU while bailer turbidity values ranged from 5 to >200 NTU (Puls et al., 1992). Repeated insertion and withdrawal of the bailer caused significant surging, mixing, and aeration, even when operated carefully. Furthermore, any results obtained with the bailer were determined to be extremely operator-dependent and therefore quite variable (Puls et al., 1992).

Another field parameter study by Puls compared only peristaltic, submersible, and bladder pumps (Paul and Puls, 1992). In one well, peristaltic and submersible pumps achieved indicator parameter equilibrium in three casing volumes; bladder pumps required 14 casing volumes. In another well, the peristaltic pump required one casing volume to attain parameter stability, the submersible pump two casing volumes, and the bladder pump eight casing volumes.

Parker et al. (1992) collected VOC samples at 100 ml/min with bladder and submersible pumps. Statistical analysis of results did not identify any differences between these sampling devices.

In a summary of technical literature evaluating sampling devices, Parker (1994) concluded that bladder pumps provided the best recovery of sensitive parameters. Parker further stated that pumping rates and flow control, as well as dedicated sampling devices, may provide improved performance from other sampling devices.

The DTG states that the use of bailers to purge monitoring wells generally should be avoided (EPA, 1992b). The DTG also states that bladder pumps and centrifugal pumps are suitable for all applications. Open bailers are not suitable for collecting samples for analysis of pH, redox potential, dissolved gases, VOCs, total organic carbon (TOC), total organic halogens (TOX), and gross alpha/gross beta (EPA, 1992b). A summary of pump type advantages and limitations is provided in Table 5-3.

5.5.1.8 Dedicated vs. Portable Systems

None of the reviewed technical literature directly compared dedicated and portable pumping systems. However, most researchers commented on the need to minimize disturbance of groundwater in order to collect representative samples. In addition, insertion and removal of devices through the stagnant water column above the well screen causes mixing of the stagnant and active waters. Disturbance, in terms of turbidity, is directly related to the size of the sampling device inserted into the well. These observations argue strongly for dedicated sampling equipment as the optimal and perhaps most efficient manner to collect a representative groundwater sample (Puls et al., 1992; Parker et al., 1992).

TABLE 5-3
PUMP AND BAILER APPLICATIONS/ADVANTAGES AND LIMITATIONS

Applications/Advantages	Limitations
BAILERS	
► Constructed from PVC, polyethylene, stainless steel, or Teflon™; bailer material can be selected according to the water chemistry ► Inexpensive, portable or dedicated, and easy to clean and use	► Generally not suited for purging wells greater than 100 feet deep ► Can cause agitation of formation water which can alter original water chemistry or mobilize naturally immobile constituents ► The transfer of water sample from the bailer into a sample container may significantly alter water chemistry ► The use of bailers to remove large quantities of water can be time consuming ► Difficult to determine the exact location in the water column from which a bailed sample has been collected ► EPA guidance indicates that bailers are unsuitable for well purging, require very careful operation and sample handling precautions under field conditions, and that field performance is questionable
BLADDER PUMPS	
Applications/Advantages	Limitations
► Constructed of stainless steel and/or Teflon™ makes bladder pumps suitable for sampling almost all types of constituents in groundwater ► Portable or dedicated ► Pumping rates can be easily adjusted to match most well yields ► Pump bladders prevent contact between the water sample and the compressed gas used to power the pump ► EPA guidance indicates that bladder pumps are expected to provide both efficient well purging and representative samples over a range of conditions with minimal difficulty in field operations	► Large volumes of air may be required to operate pump over a long period (may limit use of bottled gas) ► The pump bladder could rupture, requiring replacement ► Bladder pumps do not provide continuous flow; surging and/or high flow velocities at the pump intake could disturb natural groundwater flow conditions

TABLE 5-3 (Con't)
PUMP AND BAILER APPLICATIONS/ADVANTAGES AND LIMITATIONS

Applications/Advantages	Limitations
SUBMERSIBLE PUMPS	
Applications/Advantages	Limitations
► Generally constructed from stainless steel materials, so may be suitable for most wells where metals are not contaminants of concern ► Portable or dedicated ► Flow rates can be adjusted to match all but the lowest groundwater flow velocities	► High levels of suspended solids may clog the pump. Particulates may damage pump valving unless the intake is screened ► High pumping rates may mobilize normally immobile constituents ► Extremely low pumping rates may cause overheating and pump failure ► Overheating could volatize organic compounds with high Henry's Law constants
GAS-DRIVEN PISTON PUMPS	
Applications/Advantages	Limitations
► Generally constructed from stainless steel so may be suitable for wells where metals are not contaminants of concern ► Flow rates are adjustable to match most groundwater flow velocities ► Provide continuous flow at depths greater than most other sampling devices ► Portable or dedicated	► Valving mechanism may cause a series of pressure drops in the samples that could cause degassing or pH changes ► Pump piston assemblies are complex and may not be field-repairable ► Particulates may damage pump valving unless the intake is screened ► EPA guidance indicates that positive displacement pumps are suitable for well purging, but sampling performance is very dependent on specific design and operational details
CENTRIFUGAL PUMPS	
Applications/Advantages	Limitations
► Suitable for low flow applications (0.1 L/min) ► Generally constructed from stainless steel and Teflon™ materials, so may be suitable for most wells where metals are not contaminants of concern ► Portable or dedicated	► Centrifugal action may cause volatilization or degassing

TABLE 5-3 (Con't)
PUMP AND BAILER APPLICATIONS/ADVANTAGES AND LIMITATIONS

PERISTALTIC PUMPS	
Applications/Advantages	Limitations
► Suitable for shallow wells (depth to water <25 feet) ► Flow is adjustable to very low rates ► Portable	► Requires use of elastic silicone tubing around eccentric rollers to generate suction lift; silicone is unsuitable for groundwater sampling where VOCs are present ► Suction acts directly on sample, increasing potential for degassing ► Vacuum pumps may alter groundwater chemistry, leading to colloidal formation in wells ► EPA guidance indicates that peristaltic pumps are suitable for well purging at depths to approximately 20 feet; significantly lower recoveries of purgeable organic compounds and gases will result from sampling with this device
GAS-LIFT PUMPS	
Applications/Advantages	Limitations
► Suitable for development of production wells not intended for water quality analysis ► Portable	► High pressures can result in significant redox potential and pH changes ► The introduction of air can cause volatilization of organic compounds and/or oxidation of metallic compounds ► Not dedicated ► EPA guidance indicates that gas lift devices are proven to be biased sampling mechanisms for a range of chemical constituents, and are not recommended for any type of groundwater sampling
GAS-DRIVEN PUMPS	
Applications/Advantages	Limitations
► Similar to gas lift pumps, except that gas driven pumps provide linear flow conditions without excessive mixing of gas and water. A vacuum may be used to assist the flow. ► Portable	► Drive gas (and vacuum, if used) contact the water, potentially contaminating the water, or volatilizing or degassing constituents from the sample ► Not dedicated ► EPA guidance indicates that gas drive pumps may be suitable for well purging if used in conventional installations, malfunctions are difficult to assess or repair, and significantly lower recoveries of purgeable organic compounds and gases may occur depending on field conditions and operator experience

A sample that is representative of the groundwater could be obtained from the screened interval of a sampling well, without prior purging of the well, through the use of a dedicated sampling device (Robin and Gillham, 1987). Puls (1994a) also found that the most significant reductions in purge volumes have been found using dedicated systems. Kearl et al. (1993) stated that samples should be taken from dedicated sampling devices such as bladder pumps or submersible pumps. The study conducted at the Fernald site concluded that dedicated bladder pumps should be used (FERMC, 1993).

Oxidation may also impact groundwater quality analyses; use of a dedicated system may minimize oxidation. Samples collected in air are directly exposed to atmospheric gases during filtration and acidification procedures. Exclusion of atmospheric gases is recommended in suboxic and anoxic (low or no oxygen) groundwaters (Puls et al., 1992). Water samples should be taken directly from dedicated sampling discharge lines (Kearl et al., 1992). The DTG recommends that all sampling equipment be dedicated to a particular well (EPA, 1992b).

5.5.1.9 Pump Intake Location

Recommendations for placement of pump intake vary. In general, the intake should be located within the screened interval (Kearl et al., 1992; FERMC, 1993). According to Barcelona et al. (1994), intakes should be set at midscreen. Kearl et al. (1993) modifies this placement somewhat, stating that the pump intake should be located in the center of the screened interval unless depth specific samples are required. Robin and Gillham (1987) state that it is acceptable to place a dedicated sampler with its intake near the bottom of the screened interval. Additionally, the RSKERL study recommends placing the sample intake at the desired sampling point (EPA, 1992a).

5.5.1.10 Cost

Only one study directly estimated cost savings associated with low flow sampling. Using dedicated systems at a study site was anticipated to save $100 of labor costs per well per sampling event (Parker et al., 1992). As such, annual cost savings are roughly estimated at $80,000 at RFETS, assuming quarterly sampling of 200 wells. Labor savings alone would pay for equipment capital costs in two to three years. Further savings would be realized by considering the decreased volume of purge water to be handled and disposed, and by the elimination of rinsate sample analyses. According to the EPA (1991), the bladder pump is the best affordable technology to support most data quality objectives.

5.5.1.11 Field Personnel Requirements

As noted above, labor costs are anticipated to decrease if dedicated pumping systems are used, based on reduced setup time requirements at each well. However, an initial increase in field personnel requirements (and labor costs) is anticipated as field crews gain familiarity with the pumping systems and as data about the production capabilities of the wells are gained. Initially, the current two-person field crews would likely need to be expanded to three-person crews, dedicating the third person to careful monitoring of pump flow rate and water level drawdown in the well. Data acquired during this monitoring, combined with well recovery data provided in Section 6.0 of this report, will help in predicting optimal flow rates and water level drawdown for each well. The third person would be necessary for data acquisition at least during the first sampling round after pump installation. Subsequent sampling would likely require the current two-man teams.

5.5.1.12 Summary

Numerous studies in recent years have been conducted to evaluate the concept of low flow sampling. The technique utilizes low flow pumping rates to purge minimal quantities of water from the well prior to sample collection. When conducted correctly, low flow rates mimic the natural flow rate of groundwater across the well bore, there is less potential for disturbance of the chemical composition of the water, and waste generation is minimized. Ideally, the well is purged with a dedicated pump to minimize disturbance of the well from device insertion or withdrawal and contamination by sampling devices. Since there is no consensus by researchers regarding pump intake location, it appears that intake location is not a significant consideration aside from being within the screened interval and locating the intake adjacent to any identified dominant flow zone.

The viability of low flow sampling is based, in part, on the assumption that water within the screened interval of a well is representative of formation water. Several studies have evaluated low flow sampling compared to traditional techniques based on analytical results of groundwater samples. Other studies have emphasized stabilization of field-measured water quality indicator parameters as a function of volume of water purged from the wells, and the effect of various purging devices on the chemical composition of the groundwater. The research shows that indicator parameter stabilization ranged from a low of twice the volume of water contained within the purge pump and discharge tubing to a high of greater than three well volumes. In general, concentrations of chemicals in unfiltered samples collected after low flow sampling did not vary significantly from those identified in filtered samples collected following the traditional purging method. Purge pumps identified as least likely to impact the chemical characteristics of a groundwater sample were bladder pumps and submersible electric pumps. Both pump types have certain limitations. The surging discharge characteristic of bladder pumps can increase turbidity. The submersible electric pumps offer continuous flow at moderate or high rates, but are limited to flow rates above approximately 150 ml/min. Operation at low flow (below approximately 300 ml/min) rates may cause the pump to overheat. Overheating could lead to pump failure (automatic shutoff to allow cooling) or to volatilization of organic compounds with high Henry's Law constants.

5.5.2 Current Practice at RFETS

Groundwater sampling procedures used in the Groundwater Monitoring Program are provided in GW.6 *Groundwater Sampling* (EG&G, 1994d). The procedure includes requirements for equipment, purging, field parameter measurement, and sample collection. Actual field procedures currently used differ slightly from certain GW.6 recommendations. The following paragraphs outline GW.6 procedures pertinent to minimizing sediment in wells. Variations from GW.6 procedures are also described.

Equipment used for well purging and sample collection includes options such as bailers and pumps constructed of chemically inert materials. Teflon™ and stainless steel are cited as approved materials. Pumps may be peristaltic or gas-powered piston pumps. Current field practice uses Teflon™ bailers exclusively for well purging and sample collection.

Well purging is conducted at RFETS to ensure that groundwater samples are representative of formation groundwater. GW.6 states that aquifer properties, individual well construction specifications, and data quality objectives determine the sampling device (bailer or pump) to be used. If a bailer is used to purge the well, it is to be lowered slowly into the well, taking care to minimize agitation of the groundwater.

Pumps used for purging must meet the following criteria:

- Pump material and drive system must not introduce contamination to the well;
- All downhole parts to the pump must be easily decontaminated;
- The pump must include a return check system to prevent pumped water from flowing back into the well; and,
- The pump must be easy to use and not require excessive time to install, use, remove, and decontaminate.

The pump is to be positioned at the top of the water column initially, and lowered further into the well as the water column is drawn down.

In general, purging is considered complete when a minimum of three casing volumes of water has been removed from the well, and the last three field parameter measurements (monitored at one-half casing volume intervals) deviate less than 10 percent. Special procedures are followed if field parameters do not stabilize within five casing volumes, or when the well dewaters and does not recover to 90 percent of the initial static water level within 30 minutes. The purging flow rate is not to exceed the well development flow rate.

The GW.6 list of field parameters to be monitored is based on requirements in GW.5. As discussed in Section 4.2, current practice includes a shortened list of field parameters. Field parameters are to be measured at one-half casing volume intervals, with the exception of turbidity, which is measured once during the purging process at the discretion of the field crew. Current field practice includes turbidity measurements at one-half casing volume intervals. Alkalinity is measured once, at the completion of the purging.

Current practice utilizes non-dedicated Teflon™ bailers exclusively to collect groundwater samples. Samples should be and are protected, to the extent possible, from agitation or prolonged contact with the atmosphere. However, the emptying of bailers into a stainless steel collection bucket, and subsequent sample filtration from that bucket, results in significant contact of the sample with the atmosphere. Atmospheric contact likely affects concentrations of certain parameters, although variability in pouring techniques and retention time in the bucket limits the possibility of predicting such impacts without future study. Such study was beyond the scope of this Well Evaluation.

5.5.3 Field Evaluation

A field evaluation of groundwater purging and sampling techniques, and equipment, was conducted. The objective of the field evaluation was to evaluate candidate methods against current RFETS groundwater purging and sampling procedures, and to determine if the candidate methods warrant for further consideration for use at the site. The evaluation of the pumping systems was conducted both qualitatively and quantitatively. Methods evaluated were identified in the literature review (Section 5.5.1) and included low flow purging and sampling, combined with dedicated pumping systems. In the sections that follow is a description of the pump systems selected and the results of the field evaluation.

5.5.3.1 Bladder Pumps

In general, the bladder pumps are constructed from stainless steel and Teflon™ materials. The stainless steel pump bodies can vary between two and four feet long and are typically 1.75 inches in diameter. The Teflon™ bladder discharges water to the surface by squeezing the bladder with compressed air. The pump bladder is alternatively squeezed and allowed the fill through a controlled cycling of air pressure. A check ball at the bottom of the pump prevents water from discharging back into the well after each bladder compression. The pump is connected to two Teflon™ tubes. One supplies compressed air to the pump from the surface, and the other carries discharge water from the pump. A portable controller at the surface is used to control the timing (frequency) and pressure of the air supply. The controller regulates air flow by timing the passive filling and active pressurized discharging cycles. Air flow regulation allows bladder pumps to be used at varying pump depths, and allows control of the duration and intensity of the pump discharge. Compressed air is supplied to the controller by an air compressor or compressed air bottles.

5.5.3.1.1 GeoGuard MasterFlo

The GeoGuard MasterFlo bladder pump employs the basic bladder pump design described above. The GeoGuard controller features a cold-weather blowout device to remove water from the discharge line, potentially avoiding ice buildup during freezing weather.

5.5.3.1.2 Isco AccuWell

The Isco AccuWell bladder pump varies from the typical bladder pump design. Teflon™ bladders are relatively non-elastic and do not readily induce flow into the pump during the filling cycle. Typical bladder pumps therefore require full immersion to allow hydraulic head to fill the pump. The AccuWell pump surmounts this limitation by installing a second, more elastic, inner bladder that rebounds at the end of the discharge cycle, drawing the Teflon™ bladder with it and pulling water up into the pump. The AccuWell pump is described by the manufacturer as a "low submergence" pump, because the pump body does not have to be submerged in order to fill the bladder. The manufacturer claims that virtually zero submergence of the pump intake is necessary to fill the bladder. The inflow rate is controlled by the active elastic action of the second bladder, rather than by the passive filling from differential head. There are no mechanisms for controlling the pump fill (inflow) rate. It should be noted that, as of July, 1994, Isco is no longer manufacturing the AccuWell bladder pump. It has been included in this field evaluation to evaluate its particular approach to low submergence pumping. Reportedly, QED Environmental Systems, Inc. (QED) will support the AccuWell product line.

5.5.3.1.3 Marschalk Aquarius

The Marschalk Aquarius bladder pump is also a low submergence pump. It relies on a second pneumatic circuit to induce a "vacuum" cycle to draw water into the pump. The vacuum cycle can be adjusted to control the inflow rate. The Marschalk method of active bladder filling not only provides a means for low submergence pumping, it allows control over both the fill and discharge portions of pumping cycle. The pump may be modified by the addition of a drop tube for the intake, which allows the pump body to remain above the water column for low submergence operation.

5.5.3.1.4 QED Well Wizard

The QED Well Wizard bladder pump is nearly identical in design to the Geoguard pump. A modification to the pump inlet allows passive control of the inflow rate by diminishing the size of the intake aperture. This modification restricts the rate of bladder filling and allows a smoother discharge at low flow rates.

5.5.3.2 Submersible Pump

The Grundfos Redi-Flo 2 is a submersible electric pump that uses a high speed (2,000 to 22,000 rpm) electric motor to turn a pair of small diameter Teflon™ impellers. A generator is used to supply power to the pump, and a portable controller regulates voltage and frequency (Hertz, Hz). The pump is approximately 1 foot long and 1.8 inches in diameter. The electric submersible technology has the advantage of providing a smooth discharge (rather than the pulsing discharge of a bladder pump); however, it is limited by its minimum pumping rate of approximately 150 to 200 ml/min.

5.5.4 Discussion of Results

This section presents a summary of the field and laboratory analytical results of the pump evaluation. The field results discussion is divided into qualitative and quantitative evaluations. The laboratory results discussion presents a statistical analyses of analytical data.

5.5.4.1 Field Results: Qualitative Evaluation

Qualitative factors considered in judging the pump systems were:

- Ease of use and maintenance;
- Durability;
- Power requirements; and,
- Regulatory agency acceptance.

5.5.4.1.1 Ease of Use and Maintenance

In general, each of the evaluated pump systems was easy to use. The GeoGuard system is a typical design and features straightforward installation and operation. Maintenance of the GeoGuard system during the field evaluation was limited to disassembly of the pump for decontamination. The pump was simple to disassemble. Reassembly was difficult and if not done carefully poses a risk of damage to the top pump sleeve. No maintenance of the controller was performed. The GeoGuard controller has a digital readout and push buttons, and there should be some consideration given to ease of repair and parts replacement of the electronics with this unit.

The Isco system was similarly straightforward in installation and operation. The Isco pump has threaded top and bottom sleeves and is the easiest and most fool-proof of the pumps to disassemble and reassemble. The controller required no maintenance. The controller gauges and controls give analog readout.

The Marschalk unit has an atypical design. However, installation is straightforward. Operation of the Marschalk unit differs from the other bladder pumps, in that the controller offers a vacuum cycle to allow low submergence applications. Field crews noted initial difficulty in adjusting the vacuum cycle for smooth operation. However, this difficulty was overcome with experience. The vacuum cycle allows a more varied control of the timing and intensity of the pump cycles. The pump was easy to disassemble for decontamination. No maintenance of the pump or the controller was required during the evaluation. The controller is somewhat more complicated than the others due to the vacuum cycle controls. However, it gives analog readout and appears rugged. A disadvantage to the Marschalk controller is that it requires an external 12-volt dc power supply to operate solenoids for the vacuum cycle. Marschalk provides an optional portable (approximately 5 pounds in weight) rechargeable battery pack. Further consideration of the durability of the Marschalk controller is warranted because of its additional components.

The QED pump features a nearly identical design to the Geoguard pump. Disassembly of the pump for decontamination was simple; however, the pump leaked significantly after reassembly and was eliminated from the field evaluation after use in two well trials. QED representatives indicated in subsequent discussions that the type of seals used on the pumps vary according to whether the intended application is portable or dedicated. Portable pumps include seals which are intended for frequent disassembly and reassembly; dedicated pump seals are not intended for this use and should be replaced each time the pump is disassembled. The pump used in this test included the dedicated pump seal design. The QED controller was easy to use and required no maintenance. It is of an analog design.

The Grundfos electric submersible pump system is also simple to install and operate. Maintenance on the Grundfos pump was limited to disassembly and reassembly for decontamination, and was straightforward. The pump experienced one failure due to an automatic shutdown when the pump overheated. The pump is known to overheat at low flow rates (<300 ml/min) due to lack of water flow over the motor assembly for cooling. Higher flow rates provide sufficient water flow in the well to cool the electric motor. Since the pump relies on well water to dissipate heat and since the capacity to dissipate heat is diminished at low flow rates, there was a concern for the potential for the pump to raise sample temperatures to point that sample chemistry is affected. The potential effects include loss of VOCs and changes in dissolved inorganic compound concentrations.

To investigate the magnitude of the temperature rise of pumped water at low flow rates, a bench test was conducted under controlled laboratory conditions. The results of the test suggested that over a one-hour period of pumping at a rate of 175 ml/min, a temperature rise of 5 to 10 degrees Fahrenheit in the water discharged from the pump could be expected. A description of the test and the data and results generated are presented in Appendix B. The Grundfos controller required no maintenance during the field test; however, it should be noted that the manufacturer states that the pump controller unit can be damaged or destroyed by contact with water.

5.5.4.1.2 Durability

Given the two-week duration of the field evaluation, long-term testing of durability was not a consideration in this project. Each unit is designed for field application and, except for the concerns noted, appears adequate for long-term field use. Bladder pumps in particular are simple devices with few parts; industry experience with bladder pumps generally note the Teflon™ bladders as the only wear items. Warranties on the pumps and bladders differ by manufacturer. The GeoGuard bladder has a lifetime (25-year) warranty. The Isco pump and bladder is no longer manufactured, but had a 10-year warranty. The Marschalk pump and bladder is warranted for 5 years. The QED pump and bladder is warranted for 10 years.

The Grundfos electric pump is significantly more complicated than the bladder pumps, and therefore the potential for mechanical failure is greater. Pump impellers and seals in particular are wear items, and may require frequent replacement when operated in turbid conditions or when required to pump abrasive (gritty) sediments. No electric motor failures were noted in technical literature, and the pump used in this field test performed adequately after the previously-noted overheating failure. The Grundfos pump is warranted for 1 year.

5.5.4.1.3 Power Requirements

Each of the bladder pumps has similar power requirements: 100 to 125 psi of compressed air delivered at 3.5 SCFM is necessary to operate the pumps. As mentioned, the Marschalk pump requires external 12-volt dc power that can be provided by a battery pack or by using a manufacturer-supplied lead with clips for a car battery. Compressed air may be supplied from cylinders or air compressors; either method requires transport and access of the air to the well location.

Compressed air cylinders are expensive to maintain, cumbersome to use, and may present a health and safety hazard. The air provided by compressed air cylinders can be guaranteed clean, with no potential for impacts to samples. Air compressors typically require filtration in order to ensure that contaminated air is not introduced into the well. However, the bladder design of air-powered pumps prevents air contact with sample water, although the potential for air contact exists in the event of a pump bladder rupture. Additionally, air compressors or generators are typically gasoline-powered, with potential for spillage during refueling, and/or the introduction of exhaust fumes in the compressor intake. These potential problems are best addressed through careful field procedures such as remote fueling and locating gasoline-powered units downwind of sampling locations.

The Grundfos pump requires electric generator or line power for operation. A 3,500-watt generator is sufficient to operate the pump. The controller converts power to 3-phase, 25 to 220 volts ac, and controls frequency in a range from 46 to 400 Hz. Experience during the test demonstrated that the controller for the electric pump requires well-conditioned 110-volt ac power. A high quality generator is recommended.

The Grundfos Company indicated in late September, 1994 that a new controller is being developed, with a controller minimum power of 23 Hz. The lower power allows lower pumping rates and reportedly decreases heat generation at low operating speeds. Grundfos is also developing an in-line digital flowmeter, which could be connected to the controller to allow automatic regulation of pump speed to maintain specific flow rates.

5.5.4.1.4 Regulatory Agency Acceptance

As discussed in Section 5.5.1.7, bladder pumps and electric submersible pumps were identified in technical literature and regulatory agency guidance as the preferred alternatives for groundwater purging and sampling. Bailers are generally considered one of the least preferred options.

5.5.4.2 Field Results: Quantitative Evaluation

The quantitative evaluation of the pumping systems compared field parameter results from each pumping system, by well, in order to assess the feasibility of low flow purging and sampling. In all tests, purging was considered complete when field parameter stabilization criteria were satisfied. The following sections summarize flow rate, water level drawdown, and field parameter monitoring results from the tests. Field evaluation data are provided in tables in Appendix C-1, and as plots in Appendix C-2.

Well 0487 purging and sampling was attempted with the QED Well Wizard, Marschalk Aquarius, and Isco AccuWell bladder pumps. As described in Section 3.2, Well 0487 was replaced by a slightly more productive well (20591) to maintain the test schedule. Following the four well evaluation, Well 0487 was pumped with the Isco, Marschalk, and QED pump systems (Appendix C-1.1). In all cases the well dewatered after less than 1 liter was pumped at pumping rates as low as 20 ml/min (Appendix C-2.1.1). It was not possible to measure field parameter data given the limited volumes produced.

Well 41691 was purged and sampled with the GeoGuard, Isco, and Marschalk bladder pumps, as well as the Grundfos submersible pump (Appendix C-1.2). Flow rates varied between about 100 ml/min and 2,300 ml/min. Flow rates averaged about 1,200 ml/min with the GeoGuard pump, 650 ml/min with the Isco pump, 500 ml/min with the Marschalk pump, and 2,150 ml/min with the Grundfos pump. Head depressions typically ranged from about 0.1 feet to 0.4 feet (Appendix C-2.2.1). In general, head depressions increased over the duration of each test. One anomalous measurement of 0.8 feet of head depression was recorded when the vacuum cycle of the Marschalk pump controller was first initiated and flow rate temporarily increased.

The field parameters generally stable throughout the test were: pH, specific conductance, dissolved oxygen, and redox potential (Appendix C-2.2.2). Exceptions included a significant drop in DO values during the bailer purge, and unstable redox potential during the Marschalk purge. Based on information supplied by the field crew, the latter variability was likely caused by instrument failure. Temperature values generally declined throughout each test, displaying stability after about 5 minutes of purging regardless of the flow rate.

Turbidity levels observed when purging with the GeoGuard pump were consistently below 5 NTU, and exhibited a general decrease to a final value of 0.38 NTU. The Isco pump displayed a similar trend, with a final value of 0.48 NTU. Turbidity values observed in samples collected from the Marschalk pump exhibited significant variability, especially at initiation of the vacuum cycle. Turbidity generally ranged between 10 and 6 NTU, with peak values near 30 NTU recorded when the vacuum cycle was initiated; turbidity values subsequently decreased to a final value of.6 NTU. The Grundfos pump displayed turbidity values similar to those exhibited by the GeoGuard and Isco pumps, from an initial measurement near 2 NTU to a final value of 0.20 NTU. Historically, Well 41691 yields turbidity values exceeding instrument range (>300 NTU) when purged and sampled with a bailer. As shown on plots in Appendix C-2.2.3, turbidity was generally below 5 NTU at the start of monitoring. Samples were collected once turbidity stabilized, after an average of approximately 1.5 gallons purged (Appendix C-2.2.3). Using the bailed method, a sample was collected after three well volumes were purged, at which time 4.8 gallons had been removed and turbidity was measured at 257 NTU.

Well 1786 was purged and sampled with the Isco, Marschalk, and QED bladder pumps, and the Grundfos submersible pump (Appendix C-1.3). Flow rates ranged between about 500 ml/min and 2,200 ml/min, with an average flow rate of about 1,200 ml/min. Head depression ranged between 0.09 and 0.44 feet, and generally increased throughout each test (Appendix C-2.3.1).

Field parameters showed varying degrees of stability (Appendix C-2.3.2). Groundwater pH did not exhibit significant variation during purging, except during the Grundfos pump purge test, when pH declined from 8.2 to 6.3. Specific conductance generally increased through most tests, but increases were generally within 10 percent of initial values. Temperature values generally stabilized within 10 minutes of the initiation of purging, exhibiting either significant decreases or slight increases from initial values; final temperature values recorded by all purge methods ranged between 12° and 14°C. Dissolved oxygen values generally decreased slightly during purging, but usually remained within 10 percent of the initial value. The greatest variation was exhibited during the Marschalk pump test when DO values decreased from about 8 mg/L to a final value of about 3 mg/L. Redox potential was measured only during the Grundfos and Isco pump tests; redox values increased slightly during the Isco test and significantly during the Grundfos test.

Turbidity levels observed during the Isco pump test decreased from about 17 NTU to less than 5 NTU after 8 minutes of purging at about 500 ml/min, and a final turbidity value of 2.30 NTU was observed after 15 minutes of purging (Appendix C-2.3.3). Turbidity levels observed during the Marschalk pump test displayed a similar trend, from an initial value near 16 NTU to less than 5 NTU after 8 minutes of purging at about 1,400 ml/min. A final turbidity level of 0.38 NTU was observed after 50 minutes of pumping. Turbidity decreased during the QED pump test from an initial reading of about 20 NTU to less than 5 NTU after 10 minutes of pumping at about 1,000 ml/min, and a final value of 3.21 NTU was recorded after 27 minutes of pumping. For the Grundfos pump test, turbidity levels never exceeded 5 NTU. An initial value of 4.13 NTU generally decreased to a final value of 0.65 NTU after 27 minutes of pumping.

Turbidity in Well 1786 fell to the 5 NTU goal after an average purging of four gallons (Appendix C-2.3.3). The Marschalk pump skewed that average because it was the second test with that pump, and the field crew was still refining their technique. With the Marschalk excluded in calculation of the average, the average purge volume is approximately two gallons. The purge volume using the bailer was 3.9 gallons. The turbidity at the end of purge bailing was greater than 1,000 NTU.

Well 2587 was purged and sampled with the GeoGuard, Isco, and Marschalk bladder pumps, and the Grundfos submersible pump (Appendix C-1.4). Flow rates varied between 400 and 1,000 ml/min. The GeoGuard pump was operated over that full range. The Isco pump was operated between 700 and 800 ml/min, and the Marschalk pump was operated between 600 and 700 ml/min. Flow rates for the Grundfos pump varied between 800 and 950 ml/min. Head depression varied between 0.26 and 0.51 feet, but did not display any consistent trends (Appendix C-2.4.1).

Measured traditional field parameters, except temperature, generally were stable throughout each test, within the 10 percent criteria. Temperature values generally decreased to stable levels within about 10 minutes after the start of the purging (Appendix C-2.4.2).

Turbidity levels measured during the Grundfos test decreased from an initial value of 92.9 NTU to below 5 NTU after 22 minutes of purging (Appendix C-2.4.3). The final turbidity level observed during the Grundfos test was 3.52 NTU. Turbidity levels displayed during the Marschalk pump test increased from an initial value of 3.69 NTU to a peak of 19.10 NTU after 12 minutes of purging. Turbidity levels subsequently decreased to below 5 NTU after 36 additional minutes of purging; a final turbidity level of 2.54 NTU was recorded after 64 minutes of purging. The Isco pump test displayed turbidity levels below 5 NTU throughout the purge period, generally decreasing from an initial value of 3.07 NTU to a final value of 0.47 NTU after 36 minutes of purging. Turbidity levels recorded during the GeoGuard pump test generally decreased from an initial value of 7.41 NTU to below 5 NTU after 12 minutes of purging. Subsequently, one high reading of 6.32 NTU was observed after 16 minutes of pumping; the final turbidity level was 1.71 NTU, recorded after 37 minutes of pumping. Samples were collected after purge water turbidity stabilized. Turbidity fell to below 5 NTU after an average of 6 gallons were purged. The average value purged is not representative because the Grundfos and Marschalk tests in Well 2587 were the first uses of these pumps and pump control techniques had not been refined. A more representative purge volume to attain 5 NTU of turbidity is estimated at two to three gallons. Using the bailed method, 11 gallons were purged at which time turbidity was greater than 1,000 NTU (instrument over-range).

Well 20591 was purged and sampled with the GeoGuard, Isco, Marschalk and QED bladder pumps, and the Grundfos submersible pump (Appendix 1.5). Flow rates varied between about 15 and 250 ml/min, with an average of about 50 ml/min. Head depression varied between 0.05 and 0.63 feet, and correlated closely to flow rate (Appendix C-2.5.1).

Field parameters were generally either stable initially or stabilized within 30 minutes of purging at an average flow rate of about 50 ml/min. Temperature, specific conductance, pH, and redox potential all displayed consistent values from the start of the test (Appendix C-2.5.2). Of these parameters, a significant variance was observed in specific conductance values measured by the Solomat unit operated with the Marschalk pump unit. Other instruments consistently reported specific conductance values between 700 and 800 mS/cm, whereas the Solomat unit recorded specific conductance values between 1,200 and 1,300 mS/cm. Dissolved oxygen values were stable throughout the test for the Marschalk, Grundfos, and bailer tests; DO generally increased for the first 30 to 40 minutes for the Isco and QED systems, then decreased slightly for the remainder of the test. The DO measurements, though variable, were considered stable according to the 10 percent variation criteria.

Initial turbidity values generally ranged between about 15 to 25 NTU; turbidity levels recorded during the Marschalk pump test were initially below 3 NTU and decreased to a final value of 0.53 NTU after 40 minutes of purging (Appendix C-2.5.3). Turbidity levels observed during the GeoGuard pump test were 15.90 NTU, and decreased to below 5 NTU after 32 minutes of pumping at an average flow rate of about 50 ml/min. Final turbidity was 3 NTU, recorded after 60 minutes of purging. Turbidity levels recorded during the Isco pump test were initially 24 NTU, and decreased to below 5 NTU after 33 minutes of pumping at flow rates varying between 40 and 200 ml/min. The final turbidity value observed during the Isco test was 3.23 NTU, after 59 minutes of pumping. An initial turbidity level of 24.80 NTU was observed during the QED pump test; a decrease to below 5 NTU was observed after 25 minutes of purging at an average of about 80 ml/min. Final turbidity value recorded during the QED test was 2.44 NTU, after 59 minutes of purging. An initial turbidity value of 13.0 NTU was observed during the Grundfos test, however the pump failed after about 60 minutes due to overheating from the low pump rate (< 100 ml/min).

Turbidity in Well 20591 dropped to 5 NTU after purging 0.9 gallons. Note from the plot in Appendix C-2.5.3 that turbidity values produced by the Marschalk pump stabilized more quickly in this test than in the two earlier tests (Wells 1786 and 2587). Purge volume by the bailed method was 3.5 gallons and turbidity was greater than 1,000 NTU.

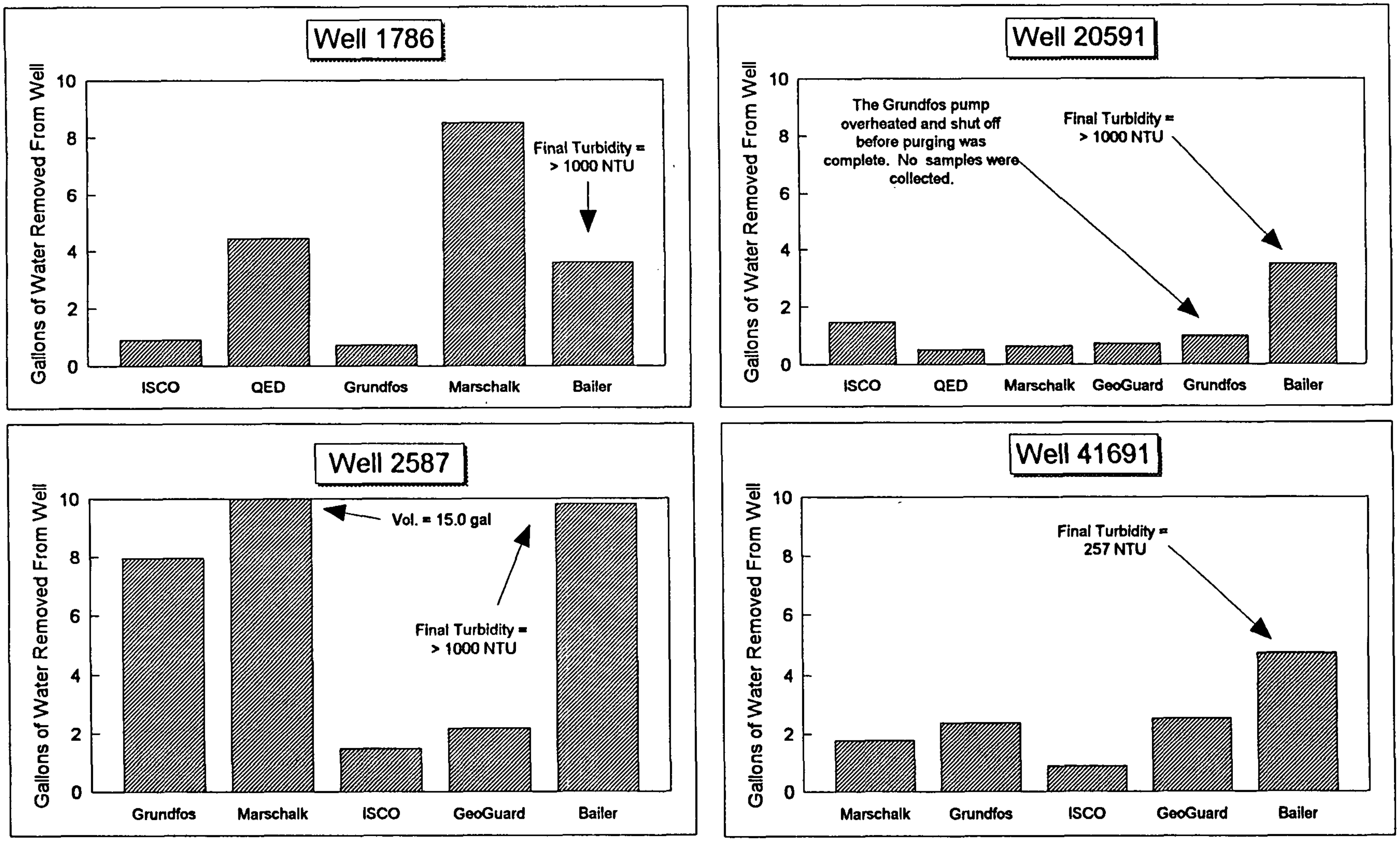
5.5.4.3 Conclusions

In general, each pump system evaluated in the field test performed adequately and was capable of producing representative groundwater samples via the low flow technique. The principle disadvantage to bladder pumps is the surging flow characteristic of the design. However, results of the field test demonstrate that bladder pumps are capable of producing as low or lower turbidity than the smooth discharging Grundfos pump. As previously discussed, the Grundfos pump experienced one overheating failure at a low flow (<150 ml/min) pumping rate. Field parameter and laboratory parameter results generally did not differ significantly between systems.

Using the EPA-designated goal of 5 NTUs as a measurement of the feasibility of low flow purging, all pump systems tested were superior to current bailer sampling techniques. Figure 5-2 depicts volumes purged from each well by each system in order to attain 5 NTUs. Also depicted is the 3-well volume purge amount removed when sampling with the bailer (without attaining the 5 NTU goal). With two exceptions, the pumping systems were able to attain 5 NTUs prior to purging 3 well volumes. The two exceptions occurred with the Marschalk pump system, and are likely the result of field crew's unfamiliarity with the relatively complex Marschalk pump controller. These exceptions occurred in the first two wells sampled with the Marschalk system. Subsequent wells met the 5 NTU goal at lower volumes (i.e., within the range of the other pumps), indicating that field crew's increased familiarity with the Marschalk system improved performance.

Based on observations during the field evaluation, wells producing less than 50 ml/min are considered incapable of real-time low flow purging and sampling. Those wells would require purging one day and sampling succeeding days. Though pumps are capable of lower flows, rates

Figure 5-2
Volume Purged to Attain a Turbidity of 5 NTU



Notes:
1) Sample events for each well shown in chronological order
2) Volume purged using bailers based on minimum 3 well volumes rather than the 5 NTU limit

Date: March 1995

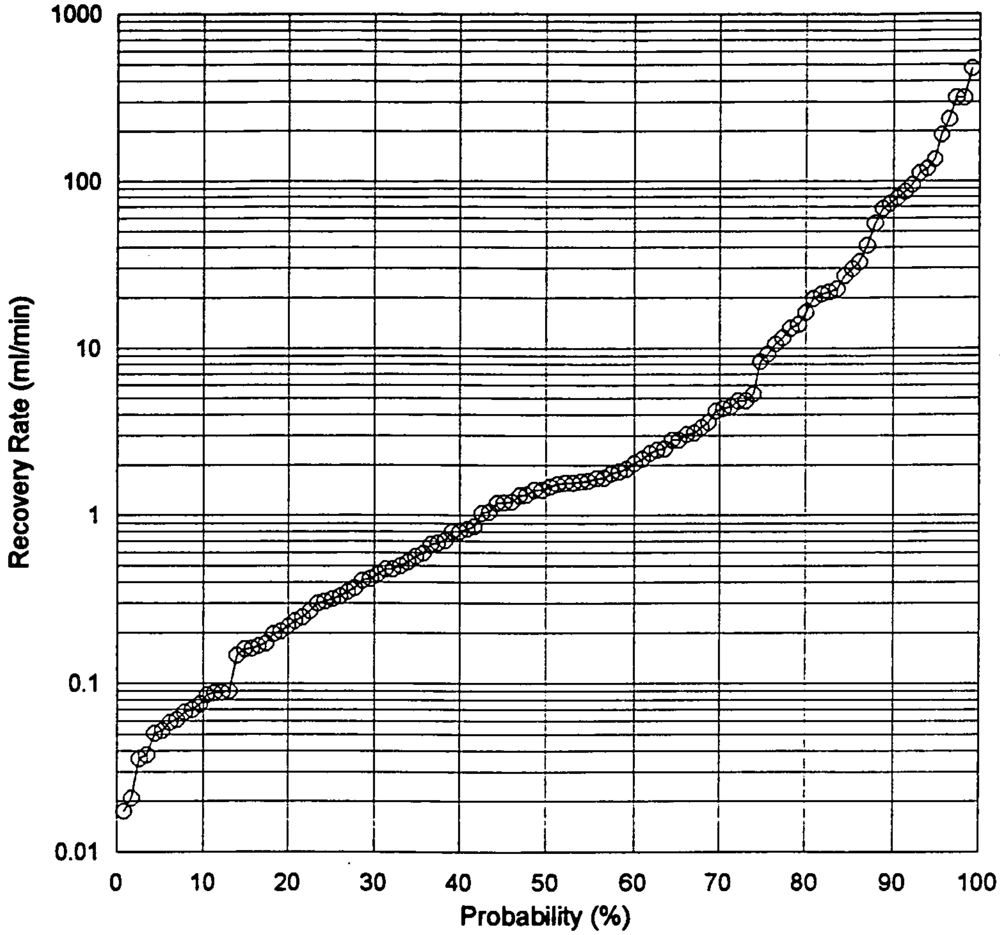
below approximately 50 ml/min result in excessive purging and sampling times, and extended residence times in discharge tubing and flow cells.

Analysis of well recovery data collected during the third quarter of 1994 (see Section 6.0) provided an estimate of the percentage of wells at RFETS that would fail to produce 50 ml/min. The estimate was based on recovery monitoring performed on the slowest of wells ("2-day" wells) on site, and on the assumption that the "1-day" wells all recover at rates faster than the 2-day wells. There are currently 194, day wells on site, which is 55 percent of the 355 wells currently in the groundwater monitoring network. Since 87 percent of the 2-day wells yield water at less than 50 ml/min (Figure 5-3), the percentage of all wells in the network that yield less than 50 ml/min is the combined percentage (55 percent multiplied by 87 percent) and is estimated at 48 percent (170 of the 355 wells in the current network). This percentage is likely higher than would be expected compared to an annual average recovery rate because recovery monitoring was conducted during the period of the year when water levels are at their lowest. Furthermore, the climate during the third quarter (summer) 1994 was significantly hotter and drier than normal.

Purge volumes using the pump systems averaged about 1 gallon at each well, discounting the anomalous initial Marschalk results. This in contrast with the approximate average volume of 5 gallons purged with the bailer. As mentioned, the bailer purges did not attain the 5 NTU goal; measured turbidity values ranged from 257 NTU to overrange (> 1,000 NTU). It is likely that pumped purge volumes would be further reduced with lower pumping rates than those used in the evaluation.

Summaries of individual pumping systems are provided in the following paragraphs.

The **GeoGuard** pumps performed adequately in most situations, with reasonable field parameter stability and acceptably low turbidity levels. In one instance (Well 2587), field crews noted that air bubbles created by the pump were affecting turbidity results. The introduction of air into the purged water could affect VOC analytical results. However, no impact on VOC analytical results for that test was noted as a result of the presence of air bubbles.



Recovery data shown are based on the rates summarized in Table 6-1 and represent rates determined from the first 2.5 gallons or less of recovery data following sampling.

EG&G ROCKY FLATS

Rocky Flats Environmental Technology Site, Golden Colorado

RECOVERY RATES IN TWO-DAY WELLS, THIRD QUARTER, 1994

DATE : MARCH 1995	FIGURE : 5-3

The **Isco** pump also performed adequately in most situations, with acceptable field parameter stability and low turbidity levels. Field crews noted that in Well 1786, the Isco pump jammed during installation and required removal of the intake screen in order to fit into the well. A tight fit was also noted with the Isco pump in Well 20591. The Isco pump is slightly larger in diameter and slightly longer than other bladder pumps. These larger dimensions could pose a problem in a higher number of wells than the other slightly smaller bladder pumps.

The **Marschalk** pump similarly delivered acceptable field parameter stability and low turbidity levels. As previously noted, in some situations the initiation of the vacuum cycle on the Marschalk controller caused a short-term increase in turbidity. This increase became less pronounced and ultimately disappeared as field crews became more experienced with operation of the vacuum cycle.

The **QED** pump produced acceptably stable field parameter results and low turbidity levels. As previously discussed, excessive leakage from the pump was noted following disassembly for decontamination, and the pump was removed from the evaluation after usage in two wells.

The **Grundfos** pump also produced acceptable field parameter stability and low turbidity levels. With the exception of the momentary (several minutes to cool) failure, this pump presented no problems.

5.5.5 Sample Analysis, Data Management and Evaluation

5.5.5.1 Sample Analysis

Groundwater samples from the field evaluation were analyzed by RFETS Contract Laboratory Program (CLP) laboratories (IT Analytical Services, Pittsburgh, Pa, and TMA/Norcal, Richmond, Ca) for the following chemical parameters:

- *Volatile Organic Compounds* - CLP Target Compound List (TCL) plus additional compounds from the EPA 524.2 list;

- *Metals* - CLP Target Analyte List (TAL) plus the additional site-specific metals: molybdenum, tin, strontium, cesium, lithium, and silicon; and,

- *Radiological constituents and radionuclides* - gross alpha/beta, uranium ($^{233/234}U$, ^{235}U, ^{238}U), strontium (^{89}Sr and ^{90}Sr combined), plutonium ($^{239/240}Pu$), americium (^{241}Am), and cesium (^{137}Cs).

Strontium-89/90 and cesium-137 were not reported for two samples collected from Well 20591 because they were not requested on the chain-of-custody documentation.

5.5.5.2 Data Management

Laboratory analysis results for the field evaluation were received in hard copy format and entered into a relational database. A separate database was prepared for each type of analysis (VOCs, metals, and radionuclides). The record structure of each database was designed to be compatible with Rocky Flats Environmental Database System (RFEDS) for future transmittal of the results. The structure of the database is summarized in Table 5-4.

The analytical results were 100 percent verified for database entry accuracy, in accordance with technical procedures, and were corrected as necessary. Results were extracted from each database into an Excel 4.0 spreadsheet for statistical evaluation, formatting, and presentation.

5.5.5.3 Data Evaluation

Data evaluation of the test results consisted of the following:

- Direct comparison of low flow filtered and unfiltered sample results, bailed filtered and unfiltered results, and historical bailed unfiltered and filtered results; and,

- Calculation of Student's t-test probabilities between filtered and unfiltered samples collected using low flow sampling techniques. The use of the t-statistic enables an objective comparison between the filtered and unfiltered samples. A 95 percent confidence limit was used to identify probability of statistically significant differences in results.

TABLE 5-4
DATABASE STRUCTURE

Field Name	Character Length	Field Type	Description/Contents
Well	7	Character	RFETS Groundwater Monitoring Well Identifier
Sample Date	8	Date	Sample Collection Date
Sample Number	13	Character	RFEDS Sample Identifier
Parameter Name	32	Character	Parameter Name As Listed On The As-Received Laboratory Report Form
Result	11	Numeric	Analytical Result For The Parameter
Result Qualifier	6	Character	Concentration Qualifier Assigned By The Laboratory (Allowable Values: Blank, U, J, or B)
Lab Qualifier	6	Character	QC Qualifier Assigned By The Laboratory (Applicable For Inorganic Analyses)
Error	11	Numeric	Two Sigma Counting Error Reported By The Laboratory (Applicable For Radiochemical Analyses Only)
Unit Measure	6	Character	The Measurement Units For The Parameter Result

Notes:

RFETS - Rocky Flats Environmental Technology Site
RFEDS - Rocky Flats Environmental Database System
V - Laboratory Qualifier; undetected
J - Laboratory Qualifier; Detected, but below Practical Quantification Limit
B - Laboratory Qualifier; Detected in Laboratory Blank
QC - Laboratory Qualifier; Quality Control Sample

5.5.6 Laboratory Results

Summary tables and graphs detailing laboratory results are included in the Appendix D.

- Appendix D-1 contains tabulated comparisons of filtered and unfiltered metals results and graphical comparisons of selected metals (aluminum, iron, lithium, manganese, selenium, and zinc).
- Appendix D-2 contains similar tabulated results and graphs for selected filtered and unfiltered radionuclides (gross alpha, gross beta, americium-241, plutonium-239/240, strontium-89/90, and uranium-233/234).
- Appendix D-3 contains tabulated results and graphs for selected VOCs (carbon tetrachloride, trichloroethene, tetrachloroethene, and total VOCs).
- Appendix D-4 contains a comparison of field evaluation results with Rocky Flats groundwater quality standards.

5.5.6.1 Metals

The following sections include a statistical analysis of the probability that data sets are from the same distribution. It should be noted that limited sample sizes may have an effect on the variability of the statistical analysis. Other factors in the variability of the statistical results are the possibility of differing detection limits, results at or near the detection limit, the use of quantitation limits when a result was reported as zero, differing numbers of results reported for filtered and unfiltered samples, and, for radionuclides, the proximity of the analytical results to the counting error.

5.5.6.1.1 Comparison of Low Flow Sampling Results

Results for low flow samples were compared by calculation of the Student's t-test value between filtered and unfiltered results. The results from each pump test and analytical fraction (filtered vs. unfiltered) were pooled together by well for the comparison. The analysis consisted of a paired t-test (one-tailed) between sample means. The t-test determines compatibilities between paired data sets and provides a measure of the probability that the data sets come from the same distribution.

Table 5-5 presents a summary of the calculated t-test probabilities, based on a 95 percent confidence limit. Overall, the metals results compare favorably with the exception of aluminum (Well 2587), magnesium (Well 41691), and iron (Wells 2587 and 20591). These differences are discussed in the following paragraphs.

For Well 2587, unfiltered aluminum results ranged from 14.6 mg/L to 33 mg/L (see Appendix D-1), while three of four filtered sample results were reported as non-detects. Unfiltered iron results ranged from 22.2 mg/L to 68.5 mg/L, as compared to filtered results ranging from 5.5 mg/L to 10.6 mg/L. This results in highly different mean values due to the higher overall unfiltered results and the high percentage of non-detects in the filtered aluminum samples. The difference in results does not appear to be due to turbidity differences since turbidity results observed prior to sampling were within acceptable ranges (ranging from 0.5 to 3.5 NTU when measured with the Hach 2100P).

For Well 20591, unfiltered iron results ranged from 26.8 mg/L to 64.1 mg/L as compared to filtered results ranging from 5.8 mg/L to 48.4 mg/L. Turbidity results for these wells were also within acceptable limits (ranging from 0.53 NTU to 3.23 on the Hach 2100P).

For Well 41691, unfiltered magnesium results (16.4 mg/L to 16.8 mg/L) and filtered results (16.4 mg/L to 17.5 mg/L) are only slightly different. However the difference is sufficient to cause the t-test probability to be just slightly less than the 0.05 (corresponding to the 95 percent confidence level) limit at 0.0427.

The average pH for the four wells ranged from 6.76 to 7.24. These conditions, along with intermediate redox values, would likely result in metals being present as compounds with low solubility. Iron would most likely take the form of $FeOH_3$, a solid, which would result in differing iron concentrations in filtered and unfiltered samples.

TABLE 5-5
RESULTS OF T-TESTS BETWEEN FILTERED AND UNFILTERED LOW FLOW PUMPED SAMPLES

Parameter	Well Identification			
	1786 (n=4)	2587 (n=4)	20591 (n=3)	41691 (n=4)
	t, probability			
Aluminum	0.0910	**0.0323**	0.2113	0.4331
Antimony	0.3378	0.2757	0.3856	0.5000
Barium	0.2511	0.2728	0.2204	0.1061
Calcium	0.2342	0.3944	0.1431	0.0252
Iron	0.0726	**0.0274**	**0.0218**	0.0702
Magnesium	0.2372	0.2985	0.2166	**0.0427**
Manganese	0.1955	0.1955	0.0741	0.0836
Nickel	0.1392	0.1433	---	0.1350
Potassium	0.2668	0.3152	0.3658	0.2177
Selenium	0.3261	0.1955	---	---
Sodium	0.2656	0.3653	0.3297	0.0883
Vanadium	0.1955	0.3188	0.2113	---
Zinc	0.4602	0.5000	0.0532	0.1187
Molybdenum	0.1028	0.1955	0.2113	0.1955
Strontium	0.2728	0.4765	0.2610	0.0844
Lithium	0.2113	0.4170	0.2278	0.1455
Silicon	0.1491	0.0856	0.1205	0.0688
Gross Alpha	0.4701	0.2773	0.4973	0.2559
Gross Beta	0.3772	0.3754	**0.0310**	0.1865
U-233,234	0.0812	0.4442	0.3382	0.4865
U-235	0.2319	0.1981	0.2437	0.2003
U-238	0.2258	0.4192	0.0572	0.4460
Sr-89,90	0.0725	0.0371	---	0.4584
Pu-239,240	0.0514	0.3042	0.2643	0.2728
Am-241	0.2382	0.5000	0.3017	0.5000
Cs-137	0.1323	0.1368	---	0.1946

NOTES:

Values represent probability that the data sets came from the same distribution. Values less than 0.05 (denoted by bold number and shading) indicate a high probability that the data sets did not come from the same distribution.

(1) indicates all results were non-detects therefore no probability value could be calculated.

(2) indicates insufficient data were available to calculate t-values.

5.5.6.1.2 Comparison of Low Flow and Bailed Sampling Results

Direct comparison of low flow and bailed well sample results shows little difference in filtered results but, as would be expected, large differences in unfiltered sample results. Appendix D-1 provides a tabular summary and graphs of selected parameters. Notable differences between low flow unfiltered and bailed unfiltered samples are reported for aluminum, barium, chromium, cobalt, iron, lead, manganese, nickel, vanadium, zinc, strontium, and silicon. Results are summarized in the tabular summary provided in Appendix D-1.1; graphs showing the comparison between aluminum, iron, lithium, manganese, and zinc are provided in Appendix D-1.2. The large differences between results from the two sampling techniques are largely due to turbidity levels measured at the time of sampling. Turbidity levels from bailed samples for all but one of the wells (Well 2587) exceeded 300 NTU (exceeded the working range of the instrument). For Well 2587, turbidity levels were measured at 35 NTU at the time of sampling.

5.5.6.2 Radiochemical Parameters

Table 5-5 lists the radionuclide analyses that were requested. The uranium, plutonium, and americium isotopes are alpha particle emitters, and their activity also contributes to the gross alpha results. In addition to these alpha emitters, there are many other isotopes which also emit alpha particles and therefore contributed to the gross alpha result, but were not reported for this study.

5.5.6.2.1 Comparison of Low Flow Sampling Results

Results for radiochemical analyses between the low flow filtered and unfiltered data were also compared by calculation of paired Student's t-test probabilities. Results of the comparison are provided in Table 5-5 using a 95 percent confidence limit, and show good comparability between the two data sets, with the exception of results for gross beta for Well 20591. The probability that results for gross beta are from the same distribution is 0.031, as compared to the limit of 0.05. The two gross beta data sets from Well 20591 differ slightly, ranging from 12.13 pCi/L to 15.85 pCi/L for filtered samples, and from 10.35 pCi/L to 14.62 pCi/L for unfiltered samples. Since turbidity levels were acceptable during sampling, the difference may be due to a slight matrix interference during analysis. Gross beta measurements are highly sensitive to the quantity of solids present in the sample. Higher solids concentration results in a shielding effect during counting causing a lower count rate than for samples with less solids content. It is possible that this shielding impacted the gross beta analysis for the Well 20591 samples, since unfiltered samples would tend to have a slightly higher solids content per unit volume than filtered samples simply because of turbidity.

While the turbidity levels achieved during the sampling were generally less than 5 NTU, there are sorption factors that can produce different results between filtered and unfiltered samples. Strontium and plutonium have K_d values that indicate they have a tendency to sorb to soil and clay particles. The tendency of strontium and plutonium to sorb may result in greater variability in analyte concentrations between the filtered and unfiltered samples.

5.5.6.2.2 Comparison of Low Flow and Bailed Sampling Results

Comparison of pumped and bailed filtered results was accomplished by pairing the single bailed result with each of the pumped results and determining the t-test probability. The limited sample size available from the filtered bailed results introduces uncertainty to the statistical analysis of the comparison of distributions.

Results of the paired Student's t-test probabilities for filtered and unfiltered radiological samples are provided in Table 5-6 and Table 5-7, respectively. Comparison of low flow and bailed filtered samples shows differences between the results for the following analytes:

- Well 1786: uranium-233/234, uranium-238, and strontium-89/90;
- Well 2587: uranium-233/234, uranium-235, and strontium-89/90;
- Well 20591: gross beta, uranium-233/234, and uranium-238; and,
- Well 41691: gross beta, uranium-233/234, uranium-235, americium-241, and cesium-137.

TABLE 5-6
RESULTS OF T-TESTS ON FILTERED LOW FLOW PUMPED AND FILTERED BAILED RADIOLOGICAL SAMPLES

Parameter	Well Identification			
	1786	2587	20591	41691
	t, probability			
Gross Alpha	0.3617	0.0728	0.4767	0.1016
Gross Beta	0.1910	0.3065	**0.0087**	**0.0195**
U-233,234	**0.0070**	**0.0107**	**0.0432**	**0.0252**
U-235	0.3852	**0.0023**	0.1588	**0.0335**
U-238	**0.0077**	0.1258	**0.0207**	0.2443
Sr-89,90	**0.0069**	**0.0001**	---	0.0503
Pu-239,240	0.3188	0.3021	0.1603	0.0908
Am-241	0.1076	0.3914	0.5000	**0.0231**
Cs-137	0.1992	0.1324	---	**0.0227**

NOTES:

Values represent probability that the data sets came from the same distribution. Values less than 0.05 (denoted by bold number and shading) indicate a high probability that the data sets did not come from the same distribution. This is likely due to a high degree of uncertainty because of analytical results at or near the method counting error.

"---" indicates insufficient data were available to calculate t-values.

TABLE 5-7
RESULTS OF T-TESTS ON UNFILTERED LOW FLOW PUMPED AND UNFILTERED BAILED RADIOLOGICAL SAMPLES

Parameter	Well Identification			
	1786	2587	20591	41691
	t, probability			
Gross Alpha	**0.000485**	**0.0000119**	**0.0000151**	**0.0000264**
Gross Beta	**0.00000118**	**0.00000652**	**0.0000489**	**0.000000819**
U-233/234	**0.0453**	**0.00381**	**0.00147**	0.116
U-235	0.252	0.433	**0.00299**	0.209
U-238	0.0750	**0.00660**	**0.000666**	**0.0239**
Sr-89,90	**0.00118**	0.222	0.00	0.449
Pu-239,240	**0.0459**	**0.0177**	**0.0000132**	**0.00226**
Am-241	**0.000617**	**0.000604**	**0.000331**	**0.000289**
Cs-137	0.336	0.474	0.00	**0.00617**

NOTES:

Values represent probability that the data sets came from the same distribution. Values less than 0.05 (denoted by bold number and shading) indicate a high probability that the data sets did not come from the same distribution. This is likely due to a high degree of uncertainty because of analytical results at or near the method counting error.

"---" indicates insufficient data were available to calculate t-values.

For unfiltered samples, notable differences between low flow pumped and bailed sample results are as follows:

- Well 1786: gross alpha, gross beta, uranium-233/234, strontium-89/90, and americium-241;
- Well 2587: gross alpha, gross beta, uranium-233/234, uranium-238, plutonium-239/240, and americium-241;
- Well 20591: gross alpha, gross beta, uranium-233/234, uranium-235, uranium-238, plutonium-239/240, and americium-241; and,
- Well 41691: gross alpha, gross beta, uranium-238, plutonium-239/240, americium-241, and cesium-137.

The differences between the unfiltered low flow pumped and bailed samples are:

- **Gross alpha and gross beta.** The bailed results are significantly higher than the low flow pumped results;
- **Uranium-233/234.** Results for the bailed unfiltered samples are slightly lower than the low flow pumped unfiltered samples. This results in a sufficient variability to cause a t-test probability of less than 0.05; and,
- **Cesium-137, plutonium-239/240, uranium-233/234, strontium-89/90, and americium-241.** All results are near or less than the measurement counting error, indicating a high degree of uncertainty in the detection of the particular constituent.

5.5.6.3 Volatile Organic Compounds

5.5.6.3.1 Comparison of Low Flow and Bailed Sampling Results

Appendix D-3 presents the tabulated results (Appendix D-3.1) for detected VOCs in all low flow pumped and bailed well samples, along with graphs (Appendix D-3.2) comparing the tabulated results with the most recent historical sample results. VOC results between each low flow pumped sample and the bailed samples are similar, with the exception of results for Well 20591. Total VOCs between all the sampling systems varied from 46 μg/L to 109 μg/L. This is likely due to the range of water temperatures observed during sampling. Table 5-8 presents a comparison of total VOC concentration versus groundwater temperature. The highest temperature observed (30.3 °C) is also correlated with the lowest total VOC concentration (46.4 μg/L). Results observed for samples collected with the Marschalk sampling system are also low in comparison to the AccuWell and bailed samples. The groundwater temperature recorded on the day of sampling with the Marschalk package was 27.4°C, which was the second-highest groundwater temperature recorded. The high groundwater temperatures may be attributed to heat generated by the pumps.

TABLE 5-8
COMPARISON OF TOTAL VOCs AND GROUNDWATER TEMPERATURE FOR WELL 20591

Sampling System	Total VOCs (ppm)	Groundwater Sample Temperature At Time Of Sampling (°C)
Geoguard	46.4	30.3
AccuWell	84	21.5
Marschalk	48	7.2
Bailer	109	13.1

6.0 MONITORING OF RECOVERY RATES IN SELECTED WELLS

Water level recovery was monitored following sampling in 194 wells selected by EG&G's Environmental Operations Management (EOM). The objectives of recovery monitoring were to obtain estimates of the time required for a well to contain sufficient water for analysis of a full analytical suite and to estimate the time required for complete recovery following sampling. Because of unusually hot and dry climatic conditions during 1994, both water levels and recovery rates were lower than normal. In addition, the monitoring was conducted during the summer season when water levels in wells have historically been at or near their annual lows. The recovery period estimates presented in this section are therefore longer than the expected annual average. Recovery monitoring commenced in May 1994. By September 2, 1994, 86 recovery tests were complete, 31 wells were dry and were not monitored, one well was inundated by the filling of pond B-5, and 76 tests were still in progress.

6.1 Field Methods for Collection of Recovery Data

Recovery rates were monitored in concert with quarterly sampling. Immediately following completion of sampling, a transducer was installed near the bottom of the well. A 10 psig In-Situ Inc. (In-Situ) transducer was used and was connected to an In-Situ Model 1000B or Model 1000C Hermit datalogger. In general the transducer monitored recovery in each well for one week. In some cases the transducer was required elsewhere before complete water level recovery was achieved, and the transducer had to be removed. In those cases water level monitoring was continued manually for the remainder of the required monitoring period. Monitoring was performed until at least 90 percent of the purging and sampling-induced drawdown was recovered. Once monitoring was complete, the transducer was removed and the datalogger downloaded. The dates and times of sampling, transducer and datalogger start and stop times, and static and final recorded water levels were recorded on a "Water Level Recovery Data Collection Sheet" field form. Also recorded on the form were intermediate manual water level measurements to verify datalogger operation and accuracy, and manual measurements taken following any removal of a datalogger during recovery.

6.2 Data Processing and Plotting

The electronic file for each well was downloaded from the datalogger to a portable computer and stored in ASCII format. The data were processed using an Excel 5.0 spreadsheet to produce graphs of the recovery. For each of the 86 completed wells, the raw and processed recovery data, together with the associated graphs, are given in Appendix F. The format of the tabulated data and graphs are described in the following sections.

6.2.1 Data Processing

The data processing spreadsheet contains header information consisting of shaded cells indicating data to be entered, and unshaded cells indicating calculated values. The header table provides both the input and the required conversions for the data needed to perform the calculations. The spreadsheet converts "Transducer elapsed time" to "Time since recovery started" by adding the time between the final bail and when the datalogger was started. Changes in water level recorded by the datalogger were converted to changes relative to the transducer reference point, which in turn were used to calculate depth of water below the top of the casing.

The volume of water stored per unit length of screened and blank-cased sections of the well is also calculated in the header table. The calculation of the volume of water stored in the screened section of the well is based on the following assumptions:

- The volume of water stored in the voids of the sandpack is "instantaneously" available to the well. Therefore this volume is treated as part of the volume of the well;
- Total volume of well = volume of casing + volume of voids in sandpack; and,
- The porosity of the sandpack = 35 percent.

The volume of water stored in the screened interval of the well, per foot, is calculated as follows:

$$Volume\ (liters) = \pi\ x\ (0.35\ r_b^{\ 2} + 0.65\ r_c^{\ 2})\ x\ 28.32$$

where:	r_b	=	radius of the borehole (feet)
	r_c	=	radius of the casing (feet)
	28.32	=	conversion from cubic feet to liters

The volume of water stored in the blank cased section of the borehole above the top of the sandpack, per foot, is given by:

$$Volume\ (liters) = \pi r_c^{\ 2}\ x\ 28.32$$

The cumulative inflow to the well is calculated from the change in water level recorded by the transducer and the storage available in the well where the water level is changing. The volume of water remaining in the casing immediately after purging is calculated in the header table. The volume of water in the well is the sum of the cumulative inflow and the volume remaining in the casing after purging. Occasionally negative inflows are indicated. This occurred when the water level fell below the transducer's reference depth.

6.2.2 Recovery Graphs

For each well the recovery data are plotted on two graphs. In each case the time axis is in elapsed hours since recovery started. The upper graph shows the number of feet of recovery of the water level above the transducer reference and the cumulative inflow to the well during recovery. The lower graph shows water level changes with respect to the top of the casing, and the total volume of water in the well.

The upper graph provides an indication of the volume, the rate of recovery in the well, and time to final recovery. The lower graph is designed more as a field tool. It can be used to identify the time when there will be sufficient water in the well for sampling, and the water levels in "feet below the top of the casing" can be used in the field to confirm that there is sufficient water in the well before sampling begins. This graph also shows (or indicates) the location of the static water level and the bottom of the well.

6.3 Results

The results of the recovery monitoring to date are shown in Table 6-1. For each of the wells, the required analyte suite (for the third quarter of 1994) is shown. Different suites require different sample volumes. For each well, the time period for recovery to the required sample volume is shown in the table. The time period for recovery to 2.5 gallons (9.5 liters) and 5.0 gallons (19.0 liters) is shown for all wells. For selected wells, the time to recover the volume for analytical suites requiring other than 2.5- or 5.0-gallon samples is also given. The time required for wells to recover to 90 percent and 100 percent is also given where possible. Some of the 100 percent recovery times were obtained by linear extrapolation of the recovery to the static water level. Where extrapolation was necessary, this is indicated beside the result. Times are given in both hours and days.

Of the 194 wells that have been or are currently being monitored:

- Recovery monitoring is completed and data plots included: 156
- Wells which recovered greater than 2.5 gallons during monitoring: 95
- Wells which recovered less than 2.5 gallons during monitoring: 59
- Wells which recovered 90 percent during monitoring: 51
- Wells which recovered 100 percent during monitoring: 36
- Dry wells which were not monitored: 37

Table 6-1
Results of Recovery Monitoring

New Well ID	3rd quarter (1994) Analyte Suite Code	Initial Volume (Gallons)	Time for recovery to required sample volume (volumes required by the various analyte suites are given below) 1.5 gallons 5.7 liters		2.5 gallons 9.5 liters		3.0 gallons 11.4 liters		3.5 gallons 13.2 liters		4.0 gallons 15.1 liters		4.5 gallons 17.0 liters		5.0 gallons 19.0 liters		5.5 gallons 20.8 liters		6.0 gallons 22.7 liters		Time period for well to recover by 90%		Time period for well to recover by 100%		
			hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	method
0586	A9	1.56	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	>43.40	>1.81	n/s	n/s	-
0786	A9	1.28	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	>266.78	>11.12	n/s	n/s	-
0986	A9	60.98	-	-	<0.11	<0.01	-	-	-	-	-	-	-	-	<0.11	<0.01	n/a	n/a	<0.11	<0.005	>60.00	>2.50	4350.00	181.25	E
1386	I	4.19	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>382.00	>15.92	n/s	n/s	-
1686	I	21.98	-	-	<1.7	<0.07	-	-	-	-	-	-	-	-	<1.70	<0.07	-	-	-	-	275.00	11.46	210.00	8.75	E
2286	I	2.40	-	-	0.48	0.02	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	0.38	0.02	n/s	n/s	-
2386	I	19.90	-	-	140.05	5.84	-	-	-	-	-	-	-	-	334.90	13.95	-	-	-	-	>478.70	>19.95	7350.00	306.25	E
2486	I	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
2586	I	24.78	-	-	56.68	2.36	-	-	-	-	-	-	-	-	233.30	9.72	-	-	-	-	>310.70	>12.95	5000.00	208.33	E
2686	I	1.46	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	103.35	4.31	14.00	0.58	f/r
2786	I	43.06	-	-	54.80	2.28	-	-	-	-	-	-	-	-	238.71	9.95	-	-	-	-	>478.70	>19.95	8350.00	347.92	E
2986	I	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
3086	I	7.45	-	-	0.09	0.00	-	-	-	-	-	-	-	-	0.78	0.03	-	-	-	-	5.08	0.21	11.00	0.46	f/r
3286	I	51.58	-	-	<0.20	<0.01	-	-	-	-	-	-	-	-	<0.20	<0.01	-	-	-	-	>214.87	>8.95	300.00	12.50	E
3386	I	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
3586	I	5.65	-	-	<0.03	<0.00	-	-	-	-	-	-	-	-	0.93	0.04	-	-	-	-	1.87	0.08	n/s	n/s	-
3686	I	1.80	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>433.37	>18.06	n/s	n/s	-
3786	I	6.61	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>286.68	>11.95	n/s	n/s	-
3886	I	1.03	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>141.70	>5.90	1500.00	62.50	E
3986	I	3.34	-	-	40.20	1.68	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	63.35	2.64	150.00	6.25	f/r
4086	I	13.01	-	-	3.10	0.13	-	-	-	-	-	-	-	-	63.40	2.64	-	-	-	-	>526.70	>21.95	5000.00	208.33	E
4386	I	2.91	-	-	1.03	0.04	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	1.93	0.08	3.00	0.13	f/r
4686	I	32.86	-	-	8.00	0.33	-	-	-	-	-	-	-	-	57.00	2.38	-	-	-	-	>215.00	>8.95	1500.00	62.50	E
5386	I	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
5786	I	1.46	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>20.13	>0.84	n/s	n/s	-
6286	I	6.42	-	-	0.45	0.02	-	-	-	-	-	-	-	-	3.15	0.13	-	-	-	-	7.32	0.31	60.00	2.50	f/r
6386	I	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
6486	I	3.60	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>262.70	>10.95	n/s	n/s	-
6786	I	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
0187	I	2.54	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>90.00	>3.75	n/s	n/s	-
0487	I	9.27	-	-	0.14	0.01	-	-	-	-	-	-	-	-	0.33	0.01	-	-	-	-	1.17	0.05	50.00	2.08	f/r
1087	I	0.73	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	53.37	2.22	80.00	3.33	f/r
1187	I	2.36	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	10.18	0.42	30.00	1.25	f/r
1287	I	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-

Table 6-1
Results of Recovery Monitoring

New Well ID	3rd quarter (1994) Analyte Suite Code	Initial Volume (Gallons)	Time for recovery to required sample volume (volumes required by the various analyte suites are given below)																		Time period for well to recover by 90%		Time period for well to recover by 100%		
			1.5 gallons 5.7 liters		2.5 gallons 9.5 liters		3.0 gallons 11.4 liters		3.5 gallons 13.2 liters		4.0 gallons 15.1 liters		4.5 gallons 17.0 liters		5.0 gallons 19.0 liters		5.5 gallons 20.8 liters		6.0 gallons 22.7 liters						
			hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	method
1487	I	10.14	-	-	0.07	0.00	-	-	-	-	-	-	-	-	0.18	0.01	-	-	-	-	0.72	0.03	3.00	0.13	f/r
1587	I	5.82	-	-	<0.07	<0.00	-	-	-	-	-	-	-	-	<0.07	<0.00	-	-	-	-	0.22	0.01	n/s	n/s	-
1687	I	23.19	-	-	<0.2	<0.01	-	-	-	-	-	-	-	-	<0.2	<0.01	-	-	-	-	>375.20	>15.63	2050.00	85.42	E
1887	I	3.46	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>433.43	>18.06	7500.00	312.50	E
1987	I	3.09	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>90.05	>3.75	2100.00	87.50	E
2187	I	5.63	-	-	0.68	0.03	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>145.08	>6.05	n/s	n/s	-
2287	I	3.49	-	-	6.07	0.25	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	14.40	0.60	150.00	6.25	E
2487	I	1.18	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>116.73	>4.86	n/s	n/s	-
3387	I	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
3487	I	22.86	-	-	38.50	1.60	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>118.55	>4.94	1100.00	45.83	E
3887	I	0.64	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>408.4	>17.02	n/s	n/s	-
3987	I	18.20	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>140.12	>5.84	n/s	n/s	-
4187	A9	27.32	-	-	107.10	4.46	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	>192.10	>8.00	n/s	n/s	-
4287	A9	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	dry	dry	-	-	dry	dry	dry	dry	-
5187	I	6.27	-	-	<0.05	<0.00	-	-	-	-	-	-	-	-	<0.05	<0.00	-	-	-	-	>136.72	>5.70	n/s	n/s	-
5487	I	2.18	-	-	93.53	3.90	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	210.00	8.75	220.00	9.17	f/r
5587	I	0.87	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>738.50	>30.77	n/s	n/s	-
5687	I	3.09	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>406.72	>16.95	n/s	n/s	-
5887	A9	11.27	-	-	<0.13	<0.01	-	-	-	-	-	-	-	-	0.16	0.01	0.17	0.01	-	-	1.40	0.06	17.00	0.71	f/r
6487	A9	4.09	-	-	0.12	0.01	-	-	-	-	-	-	-	-	4.72	0.20	n/s	n/s	-	-	2.05	0.09	7.00	0.29	f/r
6687	A9	7.00	-	-	0.08	0.00	-	-	-	-	-	-	-	-	0.38	0.02	0.42	0.02	-	-	1.05	0.04	4.00	0.17	f/r
7087	A9	6.91	-	-	250.00	10.42	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	>258.40	>10.77	n/s	n/s	-
B106089	A9	5.05	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	>214.70	>8.95	4100.00	170.83	E
B206289	A9	36.39	-	-	58.58	2.44	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	>96.92	>4.08	n/s	n/s	-
B206689	A9	11.90	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	>20.02	>0.83	n/s	n/s	-
B206789	A9	8.97	-	-	110.05	4.59	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	>238.72	>9.95	2300.00	95.83	E
B206889	A9	2.16	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	>500.03	>20.84	n/s	n/s	-
B206989	A9	3.25	-	-	b/d	b/d	-	-	-	-	-	-	-	-	b/d	b/d	b/d	b/d	-	-	b/d	b/d	b/d	b/d	-
B207289	A9	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	dry	dry	-	-	dry	dry	dry	dry	-
P207589	I	2.28	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>214.82	>8.95	n/s	n/s	-
P207789	I	1.92	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>160.08	>6.67	n/s	n/s	-
P207889	I	2.04	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>400.02	>16.67	n/s	n/s	-
P207989	I	7.92	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>116.70	>4.86	n/s	n/s	-
B208089	I	5.65	-	-	<0.12	<0.01	-	-	-	-	-	-	-	-	166.78	6.95	-	-	-	-	208.45	8.69	430.00	17.92	E

Table 6-1
Results of Recovery Monitoring

New Well ID	3rd quarter (1994) Analyte Suite Code	Initial Volume (Gallons)	Time for recovery to required sample volume (volumes required by the various analyte suites are given below)																		Time period for well to recover by 90%		Time period for well to recover by 100%		
			1.5 gallons 5.7 liters		2.5 gallons 9.5 liters		3.0 gallons 11.4 liters		3.5 gallons 13.2 liters		4.0 gallons 15.1 liters		4.5 gallons 17.0 liters		5.0 gallons 19.0 liters		5.5 gallons 20.8 liters		6.0 gallons 22.7 liters						
			hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	method
B208189	I	19.19	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>241.80	>10.078	n/s	n/s	-
B208289	I	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
B208689	I	5.53	-	-	262.75	10.95	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>502.75	>20.95	720.00	30.00	E
P208889	I	6.75	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>143.42	>5.98	n/s	n/s	-
P209089	I	6.01	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>308.40	>12.85	n/s	n/s	-
P209289	I	0.84	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>406.82	>16.95	n/s	n/s	-
P209589	I	4.33	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>262.75	>10.95	n/s	n/s	-
P209689	I	2.28	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>428.20	>17.84	n/s	n/s	-
P210089	I	7.81	-	-	183.35	7.64	-	-	-	-	-	-	-	-	n/a	n/a	-	-	-	-	>106.68	>4.45	n/s	n/s	-
P313489	IOU	8.02	-	-	0.13	0.01	-	-	-	-	-	-	0.43	0.02	0.53	0.02	-	-	-	-	1.30	0.05	3.00	0.13	f/r
P313589	IOU	6.22	-	-	4.35	0.18	-	-	-	-	-	-	14.30	0.60	20.02	0.83	-	-	-	-	23.35	0.97	100.00	4.17	f/r
P213689	IOU	2.73	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>43.53	>1.81	n/s	n/s	-
B213789	IOU	dry	-	-	dry	dry	-	-	-	-	-	-	dry	dry	dry	dry	-	-	-	-	dry	dry	dry	dry	-
P314089	IOU	1.02	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>742.68	>30.95	n/s	n/s	-
P414189	IOU	9.37	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>116.82	>4.87	n/s	n/s	-
P314289	IOU	3.17	-	-	454.68	18.95	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>718.68	>29.95	1900.00	79.17	E
P114389	IOU	8.47	-	-	6.17	0.26	-	-	-	-	-	-	20.50	0.85	25.50	1.06	-	-	-	-	98.80	4.12	330.00	13.75	E
P114489	IOU	37.35	-	-	<0.30	<0.01	-	-	-	-	-	-	<0.30	<0.01	<0.30	<0.01	-	-	-	-	4.47	0.19	5.00	0.21	f/r
P114589	IOU	31.80	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>138.80	>5.78	n/s	n/s	-
P114889	IOU	3.01	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>110.73	>4.61	n/s	n/s	-
P114989	IOU	31.08	-	-	0.10	0.00	-	-	-	-	-	-	2.87	0.12	4.20	0.18	-	-	-	-	>65.03	>2.71	180.00	7.50	E
P115589	IOU	15.06	-	-	15.57	0.65	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>41.70	>1.74	600.00	25.00	E
P115689	IOU	10.51	-	-	0.03	0.00	-	-	-	-	-	-	0.10	0.00	0.12	0.01	-	-	-	-	1.02	0.04	60.00	2.50	f/r
P416289	IOU	6.34	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>118.35	>4.93	180.00	7.50	E
P416389	IOU	15.07	-	-	<0.02	<0.00	-	-	-	-	-	-	<0.02	<0.00	<0.02	<0.00	-	-	-	-	0.35	0.01	1.50	0.06	f/r
P416489	IOU	7.21	-	-	6.35	0.26	-	-	-	-	-	-	21.02	0.88	27.68	1.15	-	-	-	-	47.68	1.99	110.00	4.58	f/r
P416589	IOU	5.68	-	-	<0.03	<0.01	-	-	-	-	-	-	0.30	0.01	0.40	0.02	-	-	-	-	0.93	0.04	6.50	0.27	f/r
P416689	IOU	5.81	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>66.70	>2.78	n/s	n/s	-
P416789	IOU	1.11	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>813.25	>33.89	n/s	n/s	-
P416889	IOU	4.68	-	-	0.23	0.01	-	-	-	-	-	-	3.37	0.14	7.20	0.30	-	-	-	-	4.87	0.20	10.00	0.42	f/r
B317189	4	n/a	-	-	n/a	n/a	n/a	n/a	-	-	-	-	-	-	n/a	n/a	-	-	-	-	n/a	n/a	n/a	n/a	-
B217289	I	35.27	-	-	<0.03	<0.01	-	-	-	-	-	-	-	-	<0.03	<0.01	-	-	-	-	>20.03	>0.84	35.00	1.46	E
P218389	IOU	1.80	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	20.02	0.83	20.10	0.84	E
P219189	IOU	2.31	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>116.75	>4.87	n/s	n/s	-

Table 6-1
Results of Recovery Monitoring

New Well ID	3rd quarter (1994) Analyte Suite Code	Initial Volume (Gallons)	Time for recovery to required sample volume (volumes required by the various analyte suites are given below): 1.5 gallons 5.7 liters		2.5 gallons 9.5 liters		3.0 gallons 11.4 liters		3.5 gallons 13.2 liters		4.0 gallons 15.1 liters		4.5 gallons 17.0 liters		5.0 gallons 19.0 liters		5.5 gallons 20.8 liters		6.0 gallons 22.7 liters		Time period for well to recover by 90%		Time period for well to recover by 100%		
			hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	method
P119389	IOU	6.73	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>238.75	>9.95	n/s	n/s	-
P219489	IOU	2.74	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>190.68	>7.95	5000.00	208.33	E
P219589	IOU	1.80	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>121.70	>5.07	n/s	n/s	-
00491	2	10.74	-	-	31.85	1.33	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>73.52	>3.06	180.00	7.50	E
00691	2	10.59	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
01291	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
01391	2	10.59	-	-	19.02	0.79	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>143.47	>5.98	n/s	n/s	-
02891	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
03191	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
03591	2	5.16	-	-	0.72	0.03	-	-	-	-	-	-	-	-	13.72	0.57	-	-	-	-	12.19	0.51	20.00	0.83	E
04091	2	4.30	-	-	3.80	0.16	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	11.80	>0.70	23.00	0.96	E
04191	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
04291	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
04491	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
04691	2	0.98	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>141.28	>5.89	n/s	n/s	-
04991	2	4.30	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>145.02	>6.04	420.00	17.50	E
05091	2	5.86	-	-	<0.02	<0.00	-	-	-	-	-	-	-	-	0.56	0.02	-	-	-	-	2.68	0.11	10.00	0.42	f/r
05391	2	8.75	-	-	0.12	0.01	-	-	-	-	-	-	-	-	0.33	0.01	-	-	-	-	2.23	0.09	30.00	1.25	E
06191	2	3.68	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>120.10	>5.00	n/s	n/s	-
06291	2	4.30	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>160.10	>6.67	4000.00	166.67	E
06391	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
06491	2	3.91	-	-	161.72	6.74	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>308.38	>12.85	1000.00	41.67	E
06691	2	8.14	-	-	9.20	0.38	-	-	-	-	-	-	-	-	116.70	4.86	-	-	-	-	325.03	13.54	450.00	18.75	E
06791	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
07191	2	11.21	-	-	<0.47	<0.02	-	-	-	-	-	-	-	-	<0.47	<0.02	-	-	-	-	>23.80	>0.99	n/s	n/s	-
07291	2	8.60	-	-	5.92	0.25	-	-	-	-	-	-	-	-	76.92	3.21	-	-	-	-	>214.92	>9.00	900.00	37.50	E
07391	2	11.51	-	-	0.32	0.01	-	-	-	-	-	-	-	-	11.18	0.47	-	-	-	-	76.68	3.20	90.00	3.75	E
07891	2	2.48	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>526.70	>21.95	13.50	0.56	E
07991	2	6.14	-	-	7.28	0.30	-	-	-	-	-	-	-	-	38.45	1.60	-	-	-	-	45.12	1.88	53.50	2.23	f/r
08091	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
08391	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
09691	2	10.90	-	-	<0.02	<0.00	-	-	-	-	-	-	-	-	<0.02	<0.00	-	-	-	-	3.02	0.13	20.00	0.83	f/r
11491	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
11691	2	4.61	-	-	0.82	0.03	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	1.82	0.08	5.20	0.22	f/r

Table 6-1
Results of Recovery Monitoring

New Well ID	3rd quarter (1994) Analyte Suite Code	Initial Volume (Gallons)	Time for recovery to required sample volume (volumes required by the various analyte suites are given below)																		Time period for well to recover by 90%		Time period for well to recover by 100%		
			1.5 gallons 5.7 liters		2.5 gallons 9.5 liters		3.0 gallons 11.4 liters		3.5 gallons 13.2 liters		4.0 gallons 15.1 liters		4.5 gallons 17.0 liters		5.0 gallons 19.0 liters		5.5 gallons 20.8 liters		6.0 gallons 22.7 liters						
			hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	method
11791	2	15.89	-	-	0.12	0.01	-	-	-	-	-	-	-	-	7.03	0.29	-	-	-	-	103.37	4.31	480.00	20.00	E
12291	2	7.52	-	-	<0.15	<0.01	-	-	-	-	-	-	-	-	0.85	0.04	-	-	-	-	>46.81	>1.95	n/s	n/s	-
13091	2	12.43	-	-	<0.03	<0.01	-	-	-	-	-	-	-	-	0.07	0.00	-	-	-	-	3.70	0.15	n/s	n/s	-
13291	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
13391	2	6.91	-	-	0.17	0.01	-	-	-	-	-	-	-	-	0.72	0.03	-	-	-	-	2.22	0.09	20.00	0.83	f/r
30991	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
31491	2	3.67	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>406.72	>16.95	n/s	n/s	-
31791	2	10.82	-	-	21.32	0.89	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>502.75	>20.95	n/s	n/s	-
32591	2	7.15	-	-	46.68	1.95	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>382.68	>15.95	n/s	n/s	-
33491	2	5.50	-	-	541.68	22.57	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>566.68	>23.61	2100.00	87.50	E
33891	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
34791	2	15.85	-	-	0.35	0.01	-	-	-	-	-	-	-	-	1.02	0.04	-	-	-	-	26.68	1.11	24.00	1.00	E
35391	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
36191	2	27.99	-	-	0.58	0.02	-	-	-	-	-	-	-	-	83.35	3.47	-	-	-	-	>143.35	>5.97	n/s	n/s	-
36391	2	8.80	-	-	4.02	0.17	-	-	-	-	-	-	-	-	190.68	7.95	-	-	-	-	>430.68	<17.95	n/s	n/s	-
36691	2	8.43	-	-	5.68	0.24	-	-	-	-	-	-	-	-	120.02	5.00	-	-	-	-	>190.70	>7.95	n/s	n/s	-
37591	2	12.05	-	-	0.03	0.00	-	-	-	-	-	-	-	-	2.02	0.08	-	-	-	-	>146.68	>6.11	330.00	13.75	E
37691	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
37791	2	11.08	-	-	0.44	0.02	-	-	-	-	-	-	-	-	21.72	0.91	-	-	-	-	n/s	n/s	3700.00	154.17	E
37991	2	7.98	-	-	0.05	0.00	-	-	-	-	-	-	-	-	0.72	0.03	-	-	-	-	16.01	0.67	30.00	1.25	E
38291	IOU	4.18	-	-	n/s	n/s	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	-	-	>233.35	>9.72	n/s	n/s	-
38591	2	3.69	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>141.70	>5.90	n/s	n/s	-
38891	IOU	19.78	-	-	dry	dry	-	-	-	-	-	-	dry	dry	dry	dry	-	-	-	-	dry	dry	dry	dry	-
38991	IOU	dry	-	-	<0.05	<0.00	-	-	-	-	-	-	0.10	0.00	0.18	0.01	-	-	-	-	>16.71	>0.70	21.50	0.90	E
39691	7	2.36	-	-	n/s	n/s	-	-	-	-	n/s	n/s	-	-	n/s	n/s	-	-	-	-	>358.72	>14.95	900.00	37.50	E
41091	OU6	4.71	11.70	0.49	70.20	2.93	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	n/s	n/s	>475.2	>19.80	n/s	n/s	-
41491	2	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
45391	6	2.33	-	-	250.00	10.42	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	133.37	5.56	140.00	5.83	f/r
10092	6	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
10192	6	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
10292	6	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
10392	6	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
10492	6	2.98	-	-	6.40	0.27	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	12.03	0.50	30.00	1.25	f/r
10592	6	2.66	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>286.70	>11.53	550.00	22.92	E

Table 6-1
Results of Recovery Monitoring

New Well ID	3rd quarter (1994) Analyte Suite Code	Initial Volume (Gallons)	Time for recovery to required sample volume (volumes required by the various analyte suites are given below) 1.5 gallons 5.7 liters		2.5 gallons 9.5 liters		3.0 gallons 11.4 liters		3.5 gallons 13.2 liters		4.0 gallons 15.1 liters		4.5 gallons 17.0 liters		5.0 gallons 19.0 liters		5.5 gallons 20.8 liters		6.0 gallons 22.7 liters		Time period for well to recover by 90%		Time period for well to recover by 100%		
			hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	hours	days	method
10792	6	1.21	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	200.00	8.33	220.00	9.17	f/r
10892	6	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	-	-	-	-	dry	dry	dry	dry	-
10992	6	1.69	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>286.70	>11.95	800.00	33.33	E
11092	6	0.64	-	-	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>238.68	>9.95	400.00	16.67	E
43392	2	3.10	-	-	0.90	0.04	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	1.33	0.06	7.00	0.29	f/r
43492	2	2.17	-	-	180.00	7.50	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	190.87	7.95	287.00	11.96	f/r
46192	2	14.43	-	-	0.42	0.02	-	-	-	-	-	-	-	-	3.02	0.13	-	-	-	-	118.00	4.92	334.00	13.92	f/r
46792	7	35.17	-	-	<0.02	<0.00	-	-	-	-	1.32	0.05	-	-	9.02	0.38	-	-	-	-	113.35	4.72	1350.00	56.25	E
50092	OU6	10.90	14.45	0.60	31.00	1.29	-	-	-	-	-	-	-	-	73.45	3.06	133.45	5.56	n/s	n/s	>143.45	>5.98	n/s	n/s	-
75092	OU6	16.42	3.70	0.15	15.95	0.66	-	-	-	-	-	-	-	-	103.30	4.30	153.30	6.39	242.00	10.08	>458.00	>19.08	7900.00	329.17	E
75292	OU6	4.45	n/s	n/s	n/s	n/s	-	-	-	-	-	-	-	-	n/s	n/s	n/a	n/a	n/a	n/a	>527.00	>21.96	n/s	n/s	-
76292	special 1	8.75	0.02	0.00	0.04	0.00	-	-	0.07	0.00	-	-	-	-	0.22	0.01	-	-	-	-	4.68	0.20	7.00	0.29	f/r
05093	OU2	11.47	-	-	<0.05	<0.00	-	-	-	-	-	-	-	-	<0.05	<0.00	-	-	-	-	2.20	0.09	22.50	0.94	f/r
22093	OU2	15.39	-	-	6.07	0.25	-	-	-	-	-	-	-	-	58.40	2.43	-	-	-	-	>233.40	>9.73	790.00	32.92	E
22393	OU2	8.01	-	-	125.00	5.21	-	-	-	-	-	-	-	-	n/s	n/s	-	-	-	-	>433.42	>18.06	5000.00	208.33	E
23193	A9	47.73	-	-	<0.03	<0.01	-	-	-	-	-	-	-	-	<0.03	<0.00	<0.03	<0.00	-	-	>20.03	>0.84	34.00	1.42	E
70293	A9	40.46	-	-	<0.03	<0.00	-	-	-	-	-	-	-	-	<0.03	<0.00	<0.03	<0.00	-	-	>28.34	>1.18	5500.00	229.17	E
70493	A9	32.41	-	-	0.11	0.00	-	-	-	-	-	-	-	-	2.11	0.09	3.35	0.14	-	-	>90.00	>3.75	115.00	4.79	E
71193	A9	8.46	-	-	5.02	0.21	-	-	-	-	-	-	-	-	41.50	1.73	54.00	2.25	-	-	334.70	13.95	500.00	20.83	E
71493	A9	3.71	-	-	2.25	0.09	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	15.68	0.65	40.00	1.67	f/r
71693	A9	3.55	-	-	0.02	0.00	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	>96.68	>40.28	n/s	n/s	-
72293	A9	3.55	-	-	<0.05	<0.00	-	-	-	-	-	-	-	-	n/s	n/s	n/s	n/s	-	-	2.38	0.10	11.00	0.46	f/r
72393	A9	15.10	-	-	<0.03	<0.01	-	-	-	-	-	-	-	-	<0.03	<0.01	<0.03	<0.01	-	-	0.23	0.01	21.00	0.88	f/r
72493	A9	dry	-	-	dry	dry	-	-	-	-	-	-	-	-	dry	dry	dry	dry	-	-	dry	dry	dry	dry	-

Notes:

- \- Volume not required
- n/s Insufficient volume when recovery complete
- dry dry well
- n/a Recovery data not yet available
- b/d Bad data (water level declined after purging was completed)
- E Extraploation
- f/r full recovery

Initial Volume" refers to the wellbore volume before sampling and includes the casing and sandpack (adjusted for porosity) volume.

7.0 GROUNDWATER FLOW PATH ANALYSIS

Methodology used for and results from a groundwater flow path analysis of RFETS are presented in this section. The primary objective of the groundwater flow path analysis is to assess the existing monitoring well network at RFETS. The groundwater flow path analysis is intended to identify major groundwater flow paths associated with contaminated regions within the unconsolidated surficial materials.

The general methodology used for this analysis was to develop a groundwater flow model for the area of interest, and then, using the results from the flow model, investigate the major groundwater flow paths using particle tracking. Particle tracking involves following the pathway of imaginary particles placed within the groundwater flow field. As the particle tracking simulation proceeds, the particles move through the groundwater system based on the groundwater velocities at each model grid node. The information to determine these velocities comes from the groundwater flow model. The particles can be tracked for any length of time. The results presented here represent 10-year travel pathways. The region used in this analysis comprises the eastern two-thirds of RFETS. This includes a large portion of the Industrial Area, and the two major drainages (Woman Creek and Walnut Creek) which drain the Site (Figure 7-1).

The following discussion is divided into two major sections. The first section discusses the groundwater flow model implementation and calibration. The second section describes the particle tracking process, the results from the groundwater flow path analysis, and presents some conclusions and observations based on the analysis. In addition, although these study areas may be included in the study area used here, results from smaller scale (Operable Unit level) model may differ from those presented because of difference in modeling scales and grid spacing.

7.1 Groundwater Flow Model

This subsection presents various aspects of the groundwater flow model used in the groundwater flow path analysis. The groundwater flow modeling is a very integral and important aspect of this

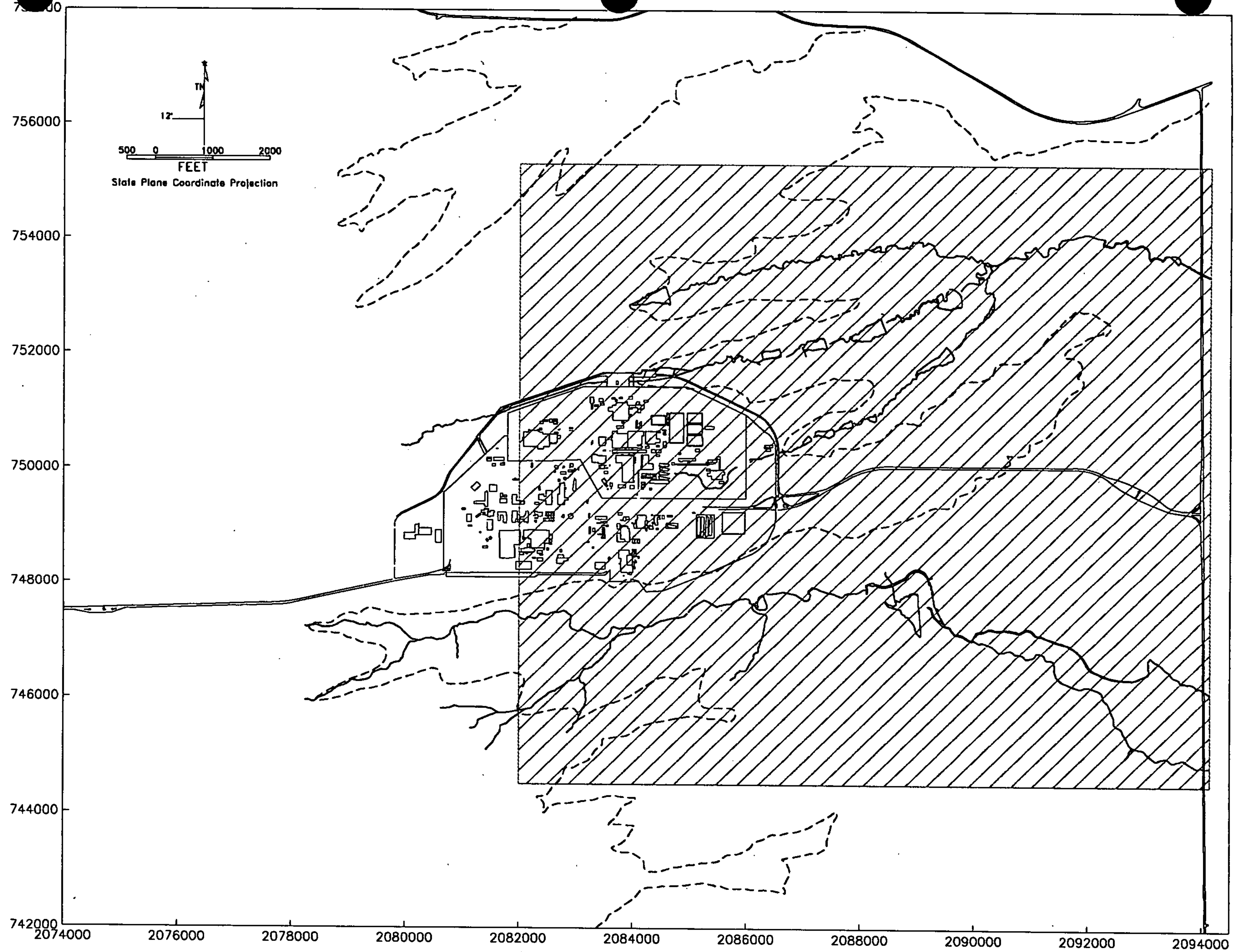


Figure 7-1. Study area location is shown by brown hatchured region. The outline of the Rocky Flats Alluvium is shown by dashed green line; streams are shown in blue.

analysis because it is the flow model which determines the groundwater flow field used in the particle tracking. Any parameters which affect the groundwater flow model will also affect the particle tracking.

7.1.1 Mathematical Modeling Code

This section discusses general aspects of the computer code used to do the groundwater flow modeling, selection criteria, and the output generated by the code.

The computer code selected for the groundwater flow modeling portion of this project was the USGS modular, three-dimensional finite-difference groundwater flow model commonly referred to as MODFLOW (McDonald and Harbaugh, 1988). A discussion of the criteria used in selecting MODFLOW for this project is presented below.

The main criteria used for selecting the computer code to use for this project were that the selected model should be:

- Able to incorporate key hydrogeologic processes and accurately represent conditions known to occur at the site;
- Able to satisfy the objectives of the study;
- Verified using published equations and solutions;
- Complete and well documented and preferably available in the public domain; and,
- Practical and cost-effective in terms of actual applications as well as resolution of uncertainty.

The MODFLOW code met each of these criteria, based on the observations listed below.

- MODFLOW is a modular program with a wide variety of packages available for simulating different hydrogeologic processes. The key hydrogeologic processes at RFETS (areal recharge, groundwater/surface-water interactions, subsurface drains, two-dimensional flow in saturated porous media) are all simulated within various MODFLOW model packages.

- The objective of this portion of the project is to provide a saturated groundwater flow model that can be used for groundwater flow path analysis of the selected study area. MODFLOW meets this objective by providing a two-dimensional simulation of groundwater flow for a grid covering the area of interest, and by providing output which can be used in a particle tracking model.

- MODFLOW is a widely used finite-difference flow model that has gained broad acceptance and recognition (Anderson and Woessner, 1992; van der Heijde, et al., 1988). In addition, MODFLOW has been verified against several problems which have analytical solutions (Anderson, 1993).

- MODFLOW is a complete package for simulating two-dimensional groundwater flow through layered porous media; no additional code is required for the flow computations. The MODFLOW model is documented in a comprehensive USGS publication (McDonald and Harbaugh, 1988), and the source code is available in the public domain.

- Several modeling pre-processors and post-processors are available for aiding in MODFLOW input data development and output analysis. The MODFLOW model is widely available and is written in standard FORTRAN 77. It can easily be implemented on any computer that has a FORTRAN 77 compiler. In addition, MODFLOW has been used for previous modeling work at RFETS. These factors provide for the practical and cost-effective application of MODFLOW to the groundwater flow path analysis project. The structure and character of the MODFLOW input and output data sets provide sufficient means for standard sensitivity analysis.

MODFLOW is a modular, three-dimensional, finite-difference saturated-flow model written in FORTRAN. Although capable of simulating vertical groundwater flow, MODFLOW is commonly used to simulate two-dimensional layered systems with varying vertical conductance between the layers. Vertical and horizontal model dimensions are defined by the thickness of the layers and the row and column spacing, respectively. The model grid is implemented in a block-centered fashion.

The groundwater flow simulations use the standard, required MODFLOW modules for basic model input (subroutine BAS1) and conductance term calculation (subroutine BCF1) (McDonald and Harbaugh, 1988). A preconditioned conjugate-gradient solver (subroutine PCG2) (Hill, 1990) was used to solve the matrix of equations generated by the finite-difference approximations of the differential equations describing groundwater flow. An optional output control module was also used to provide better control of the format and frequency of the output generated by the model.

In addition to the modules discussed above, the recharge package (subroutine RCH1AL), subsurface drain package (subroutine DRN1AL) (McDonald and Harbaugh, 1988), and streamflow-routing package (subroutine STR1RP) (Prudic, 1988) were used in the groundwater flow modeling. The recharge package was included because areal recharge through precipitation is an important factor in groundwater flow at RFETS. The subsurface drain package was incorporated to allow simulation of some of the major subsurface water control features at RFETS. The streamflow-routing package was included to incorporate groundwater/surface-water interactions into the model.

7.1.2 Groundwater Flow Model Implementation

The implementation of the simulation code selected for the groundwater flow model are discussed in this section. The implementation of the simulation code involves developing input data for the code that reflect the hydrogeologic conditions at RFETS. This section also discusses the manner in which the MODFLOW model was transferred to and executed on EG&G's computer systems.

The primary source code for the MODFLOW model was obtained from the International Ground Water Modeling Center (IGWMC) located at the Colorado School of Mines in Golden, Colorado. The IGWMC is an internationally recognized organization, which acts as a distributor of groundwater-related modeling codes and model information. The source code for the streamflow-routing package was obtained from the USGS. Additional code for the synthetic hydrograph module was taken from Plato (1993).

The FORTRAN source code files were transferred to an IBM RS6000 UNIX workstation for compilation. The IBM FORTRAN compiler for these workstations does not recognize I/O unit numbers greater than 99. The I/O unit numbers in the MODFLOW source code were changed to meet this requirement. This, and the addition of the synthetic hydrograph module (Plato, 1993), were the only changes made to the original source code. Both of these changes involve changes only to the input or output portions of the source code, and neither altered the computational aspects of the model. Additional details regarding the installation and testing of the MODFLOW model are presented in EG&G (1993c).

7.1.2.1 Implementation of the Conceptual Hydrogeologic Model

The conceptual hydrogeologic model is emulated in the computer groundwater flow model by designating input parameters appropriate for the site. The conceptual hydrogeologic model used in this study is that presented in EG&G (1993c). The current version of the groundwater flow model focuses on the waters in the unconsolidated surficial materials. It treats the Rocky Flats Alluvium, hillslope colluvium, and valley fill materials as a single, unconfined layer within the MODFLOW model. The modeling presented here represents hydrologic conditions occurring during the Spring, 1992.

7.1.2.1.1 Model Domain

The model covers an areal extent which includes a majority of RFETS Industrial Area and a large portion of RFETS Buffer Zone (Figure 7-2). The extent of the model grid nodes in State Plane coordinates is from 755000 to 744600 feet northing and from 2082100 to 2094050 feet easting. The grid is oriented with the rows aligned along an east-west direction. This orientation aligns the model grid so that the grid rows are parallel to the predominant groundwater flow direction. The grid is implemented using nodal spacings of 200, 150, 100, and 75 feet along rows and columns. A nodal spacing of 75 feet is used in the central portion of the model domain, with the spacing increasing towards the model boundaries.

The groundwater flow simulations included in this report focus on Spring, 1992 time period. This period was chosen because it is relatively recent, and because Spring, 1992 was a time of relatively high water levels at RFETS. This represents a time of important groundwater flow and transport because of large saturated thicknesses and sizable saturated extents. The conditions modeled here are not intended to represent average conditions at RFETS. These factors result in a very complex groundwater table that is not well represented by a steady-state simulation. To allow the model to equilibrate with the input parameters, the transient simulations were run for long time periods using relatively short time steps. The model was run for 3,600 one-day time steps (approximately 10 years). This simulation length was thought to be adequate to allow the model to equilibrate to the input data set.

To verify that the simulated heads had equilibrated with the input data, hydrographs showing head elevation during the simulation were developed for a number of model grid nodes. This information is presented as relative hydrographs in Figures 7-3 through 7-6. These relative hydrographs show the difference between the final head elevation and the head elevation at any given time step during the simulation. Each figure shows a series of hydrograph curves representing the modeled head at different grid cells within the same model grid row. A series of 23 hydrographs representing grid cells distributed throughout the study area are displayed in this manner. All of the grid cells represented by these hydrographs have reached an equilibrium head condition by the end of the simulation. Based on this sampling of grid nodes it is assumed that the model has equilibrated to the input data set by the end of the simulation.

7.1.2.1.2 External Processes Modeled

Some of the factors affecting groundwater flow at RFETS are not incorporated within the subsurface groundwater flow system itself. These factors are external processes which have a direct influence on the groundwater flow system. The most significant external processes included in the groundwater flow model are areal recharge, loss and gain to surface streams, and loss to subsurface drains. These factors have an important influence on the head elevations at RFETS and so influence the subsequent groundwater flow pattern.

Percolation of meteoric waters through the unsaturated zone to the water table can account for significant recharge to the subsurface groundwater flow system. There are several factors that influence this process. Evapotranspiration, the primary external influence at RFETS, may remove water held in the unsaturated zone before it has an opportunity to recharge the saturated zone. The

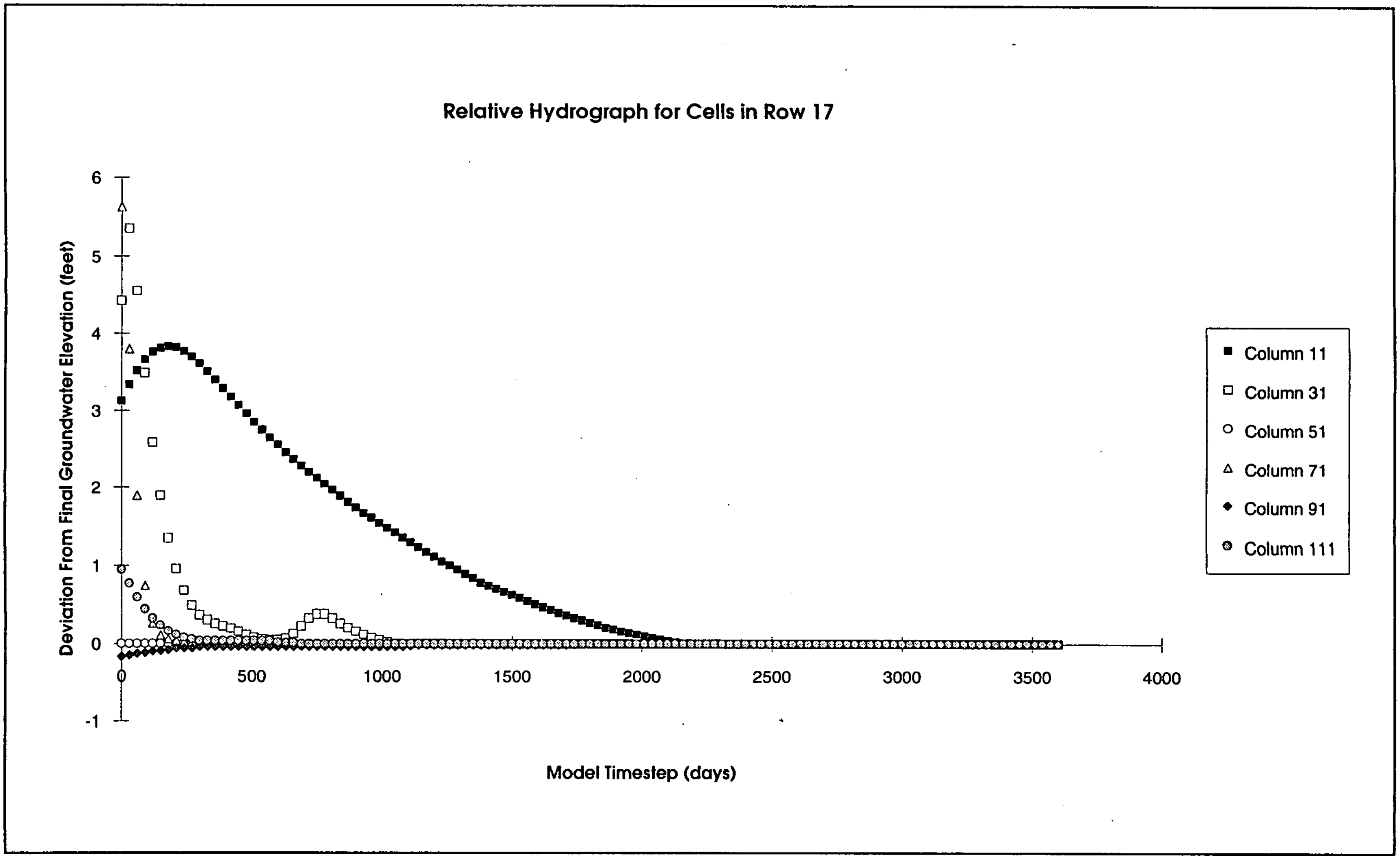


Figure 7-3. Relative hydrograph for cells in row 17 of the MODFLOW flow model.

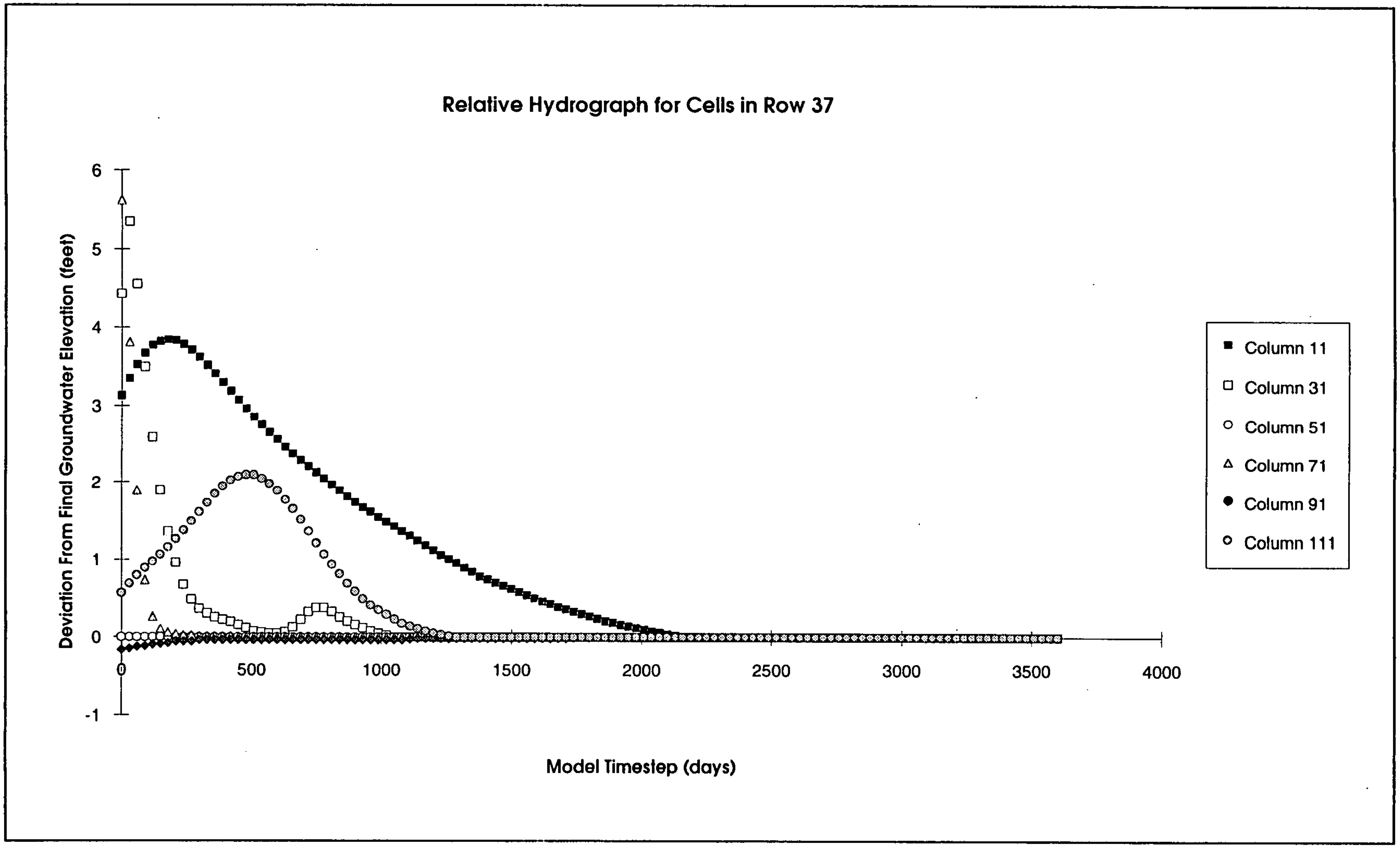


Figure 7-4. Relative hydrograph for cells in row 37 of the MODFLOW flow model.

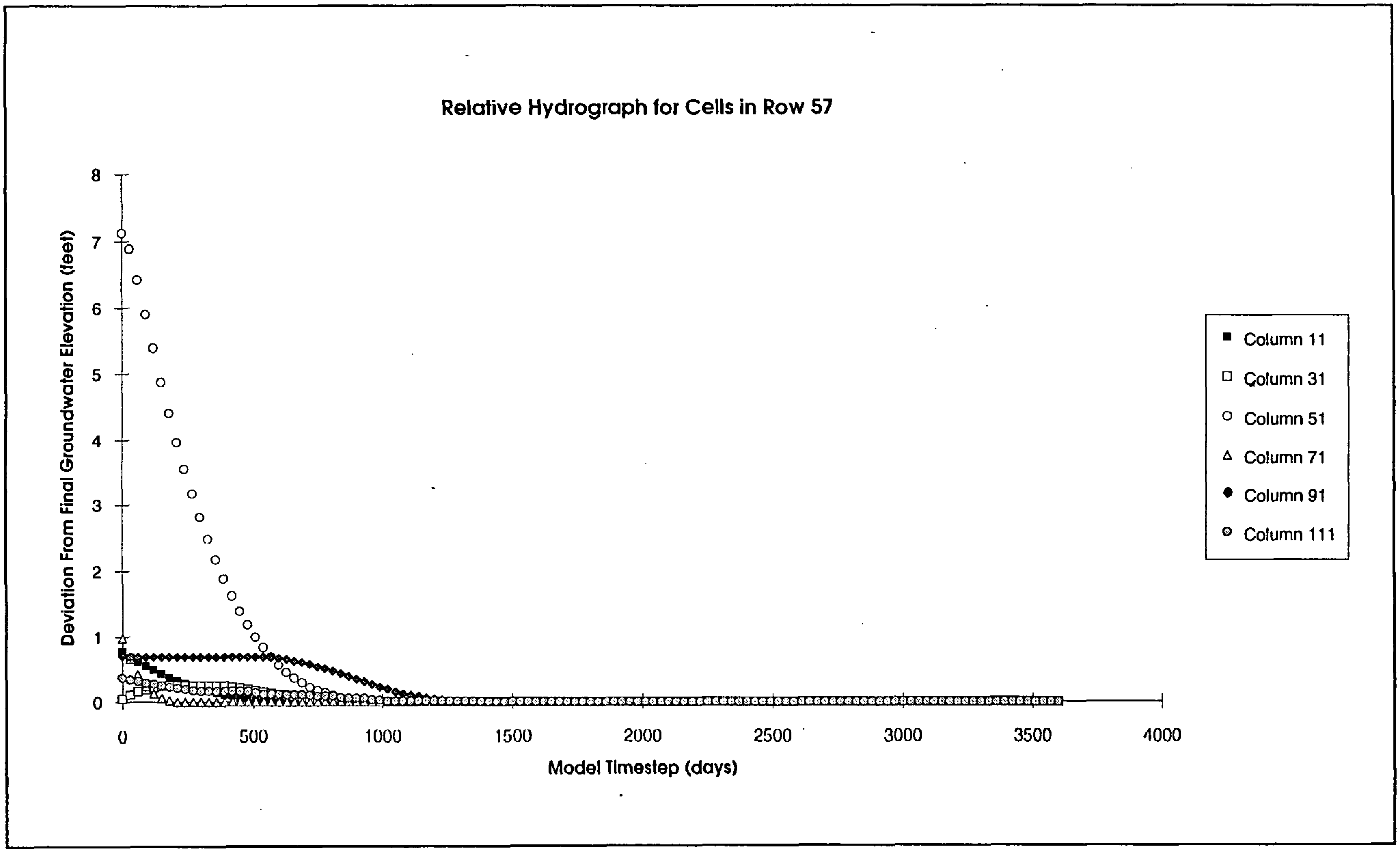


Figure 7-5. Relative hydrograph for cells in row 57 of the MODFLOW flow model.

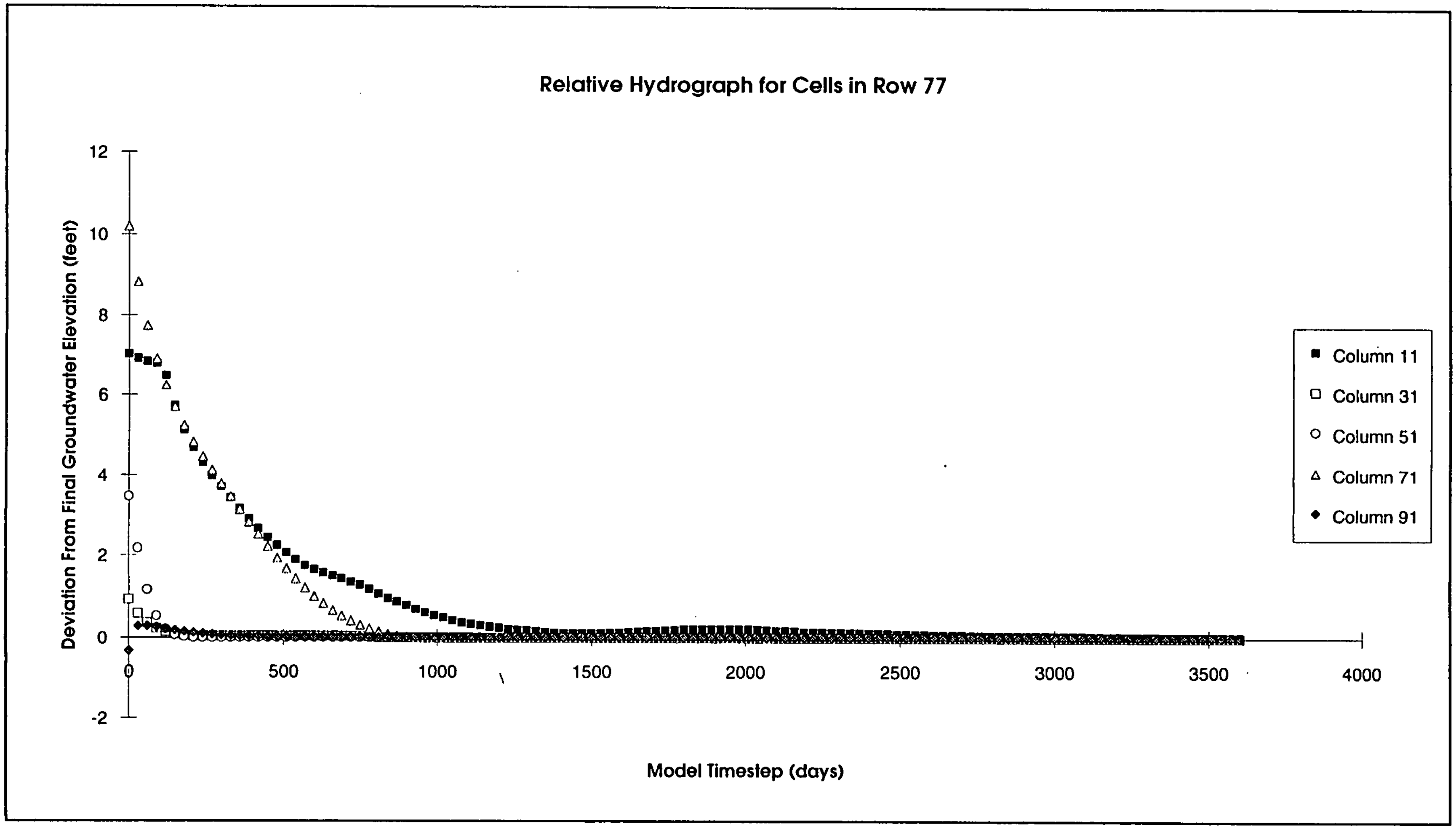


Figure 7-6. Relative hydrograph for cells in row 77 of the MODFLOW flow model.

potential evapotranspiration at RFETS has been calculated to be approximately 39 inches of water per year (Fedors and Warner, 1993). This value is approximately twice the average annual precipitation rate at RFETS. This demonstrates the large potential for water loss through evapotranspiration.

Although MODFLOW includes a module to simulate water loss through evapotranspiration, a much simpler and commonly used approach is to use the net recharge to the groundwater system. By using net recharge, only the amount of water remaining to recharge the groundwater system must be estimated. In MODFLOW, the recharge module adds an areally distributed recharge value (feet/day per unit area) into the groundwater flow calculations. The values of net recharge used in the groundwater flow model are discussed below.

The network of surface drainages that cross RFETS can transfer water to and from the groundwater system. Studies of Woman Creek by Fedors and Warner (1993) indicate that this drainage varies from gaining to losing along various segments, and that the character of an individual segment may change through time. This transfer of water volume between the surface and subsurface flow systems was simulated using the MODFLOW stream-routing package.

The stream-routing package compares the head in the stream with the head in the aquifer and computes the direction (to or from the stream) and magnitude (based on the conductance of the stream bed and head differences) of water flux. The primary drainages at RFETS (Woman and Walnut Creeks) were initially included in the model. Additional drainages were added based on simulation results during the calibration process. The only irrigation ditch currently included in the model is Mower Ditch, which is used to divert water from Woman Creek to Mower Reservoir. Mower Ditch was included in the model because a large portion of the flow in Woman Creek is continually diverted into the ditch. The other irrigation ditches that cross RFETS were not included because they are only used sporadically. Specific details regarding input to the stream-routing package are discussed below.

Groundwater recharge from ponds within the Woman and Walnut Creek drainages is included in the model using constant head cells. All of the A-series ponds (with the exception of A-5), B-series ponds, C-series ponds, and the present landfill pond are simulated in this manner. The A-5 pond is not currently included because of its small size.

Two of the major subsurface water-flow control features in place at RFETS are included in the groundwater flow model: the groundwater intercept system in place at the Present Landfill and the subsurface drain system located adjacent to the Solar Evaporation Ponds. These structures are designed to capture groundwater to prevent the spread of contaminated groundwater or to prevent groundwater from entering a potentially contaminated area. Each of these systems was simulated using the standard MODFLOW drain package (McDonald and Harbaugh, 1988).

The French Drain system located on the 881 Hillside of OU1 was not included in the present model. This system was excluded because it was believed that the influence of the French Drain would not be adequately represented in the model using the present grid-spacing. A much finer grid would be required to show the influence of this system because of the steepness of the hillside, the thin saturated thicknesses in that area, and the small size of the drain relative to the scale of the groundwater flow model. In addition, the foundation drain systems for the buildings were not included in the model. The foundation drains were excluded because their influence cannot be well represented at the scale of the modeling presented here. To incorporate the effects of these drain systems in the model would require a much finer grid-spacing. A grid fine enough to incorporate the effects of the foundation drains would not be appropriate for the region studied here.

7.1.2.1.3 Model Parameters

A review of the values or range of values of input parameters used for the groundwater flow modeling are presented in this section. Where available, RFETS field measured values were used as a basis for the input values. Appropriate literature values were used as guidance when field data were unavailable or had significant uncertainty. Some parameters had neither field data nor appropriate literature values. In these cases, professional judgement was used in estimating reasonable input values.

The input data files for MODFLOW were set up to use length units of feet and time units of days. These were the most convenient and applicable units for this task. All the data in the following discussion are presented in these units.

Hydraulic conductivity is a parameter that enters directly into the flux calculations within MODFLOW. Field and laboratory measured values of hydraulic conductivity are available for the unconsolidated surficial materials at RFETS; there is a considerable range in the values of hydraulic conductivity determined for specific material types. A summary of this information is listed in Table 7-1. Some of this variability is associated with differing test conditions and some reflects the heterogeneity of the geologic materials.

Table 7-2 provides a summary of the hydraulic conductivity values actually used in the groundwater flow model. A comparison of the values used in the groundwater flow model against the observed data (Figure 7-7) verifies that the hydraulic conductivity values used in the model are within the range of the observed data.

The initial spatial distribution of hydraulic conductivity values was taken from the final results of the 1993 RFETS site-wide groundwater flow model (EG&G, 1993c). This distribution was then adjusted during the model calibration process. In the model, hydraulic conductivity is considered to be isotropic.

MODFLOW uses values of specific yield to determine the head change in a cell based on the volumetric water flux into and out of the cell. Although estimates of specific yield are available from some of the multi-well pumping tests conducted at RFETS, these values are problematic. A multi-well pumping test conducted as part of the OU-1 Phase III investigation produced specific yield values with a mean of 0.64 (EG&G, 1993a). This value is approximately two times the maximum value expected for coarse gravel (Anderson and Woessner, 1992; Fetter, 1980). Several

Table 7-1
Summary of Observed Values of Hydraulic Conductivity

	Minimum (ft/day)	Maximum (ft/day)	Geometric Mean (ft/day)
Rocky Flats Alluvium	7.2×10^{-5}	1.4×10^{2}	4.4×10^{-1}
Hillslope Colluvium	1.2×10^{-2}	6.2×10^{1}	7.2×10^{-1}
Valley Fill Alluvium	6.0×10^{-3}	1.1×10^{2}	4.0

Source: EG&G, 1993c.

Table 7-2
Summary of Values of Hydraulic Conductivity Used in Model

Geologic Material	Minimum (ft/day)	Maximum (ft/day)
Rocky Flats Alluvium	1.0×10^{-2}	3.3
Hillslope Colluvium	1.0×10^{-1}	3.3
Valley Fill Alluvium	4.0	13

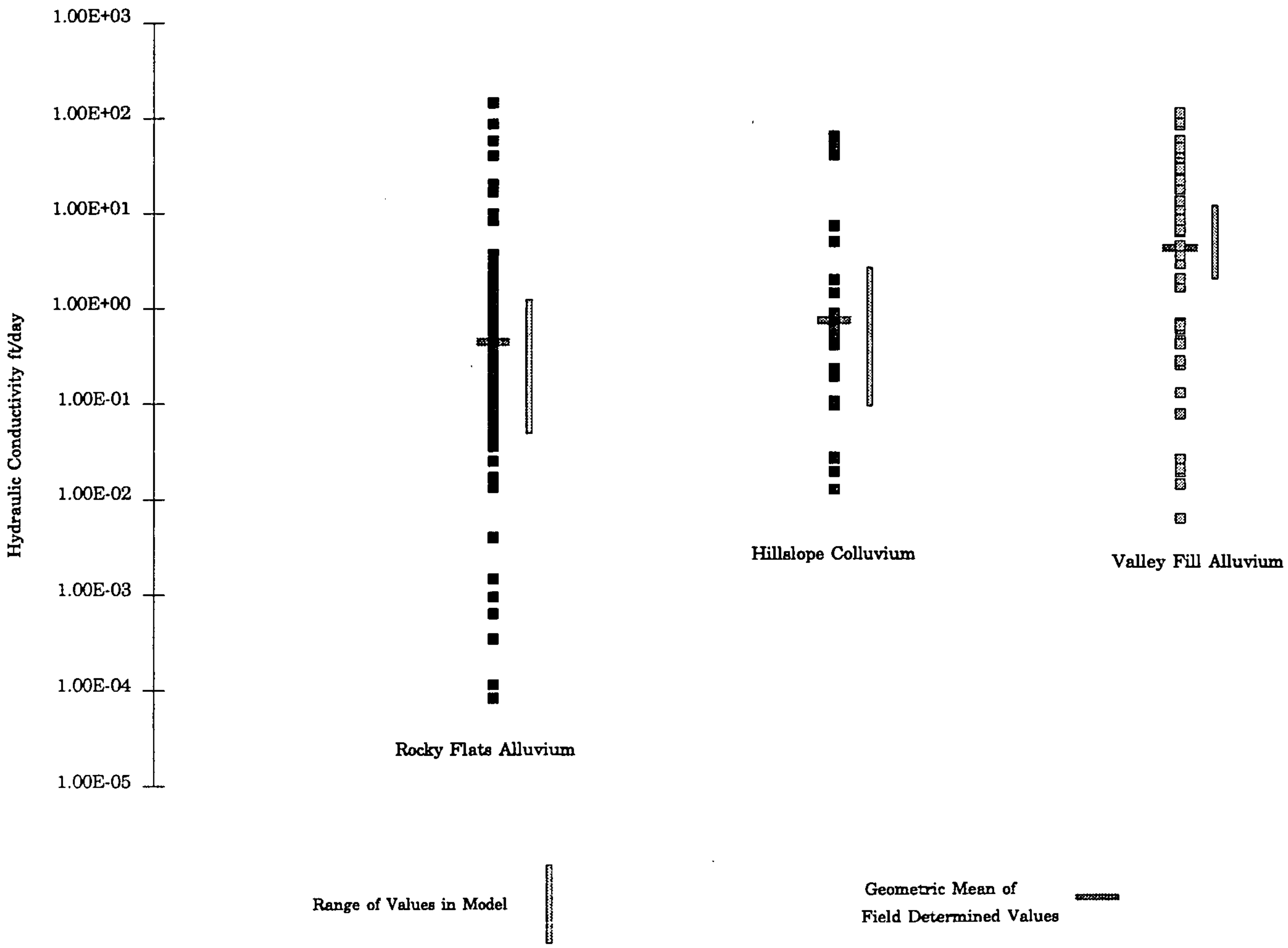


Figure7-7. Comparison of measured values of hydraulic conductivity, shown by filled squares, and the range of values used in the model, shown by vertical bars. Values are grouped by geologic media type. Geometric mean of measured values is shown by horizontal bar.

of the analyses from this study produced specific yield values greater than one, which is not physically possible. It is likely that some of the assumptions necessary for the analysis were not valid for the test conditions. A series of multi-well pumping tests were also conducted as part of the OU-2 Phase II investigations. Although the average value of specific yield (0.04) computed from this testing is plausible for the materials tested (Anderson and Woessner, 1992; Fetter, 1980), analysis of the test data indicate that the tests were not run long enough to collect data for calculating accurate specific yield values (EG&G, 1992b).

Because of the uncertainty of these values, a representative specific yield value of 0.10 was adopted for the groundwater flow model. This value is consistent with that calculated by Hurr (1976) and lies within the range of values expected for the type of materials under consideration (i.e., clay, slit, and sand) (Anderson and Woessner, 1992; Fetter, 1980). Future work involving re-analysis of previous field tests and the examination of laboratory water-retention curves will help in refining this value. This parameter was not adjusted during the groundwater flow model calibration.

As discussed above, the groundwater flow model uses a net recharge approach in incorporating recharge from precipitation. The initial spatial distribution of net recharge values was taken from the final results of the 1993 RFETS site-wide groundwater flow model (EG&G, 1993c). This distribution was then adjusted during the model calibration process. Values of net recharge used in the model ranged from 0 to 1.6E-04 ft/day. A value of zero was used for some of the highly developed areas of RFETS where large areas of low-permeability pavement restrict recharge.

The input requirements to the MODFLOW stream-routing package, as used here, and how these requirements were met, are listed in Table 7-3.

The last three parameters in Table 7-3 are used to compute the approximate stream stage. The other parameters are used in the calculation of the volumetric water flux to or from the underlying aquifer.

Table 7-3
Stream Routing Data

Input Data Required	Value Used in Model
Inflow at upstream end of stream	Assumed to be zero at model boundary
Stream stage	Assumed to be 0.5 feet
Hydraulic conductance of the streambed	Computed using the hydraulic conductivity, stream length, width, stage, and streambed bottom elevation.
Elevation of the top of the streambed	Groundwater elevation minus stage.
Elevation of the bottom of the streambed	One foot below the top of the streambed.
Width of the stream channel*	Assumed to be three feet
Slope of the stream channel*	Assumed to be 0.020
Manning's roughness coefficient (n)*	Assumed to be 0.035

*used to compute stream stage

The water inflow from upstream stream segments not explicitly modeled was considered to be zero. This is physically correct for many streams. Those streams that may have some contribution from upstream flow were set at zero until reliable stream flow data are obtained. The stream stage listed in Table 7-3 is primarily used to compute the conductance of the streambed (McDonald and Harbaugh, 1988) and the listed value was chosen as being representative. Because the inflows to all stream segments are zero, the initial stream stage actually used in the model is equal to the elevation of the top of the streambed (Prudic, 1988). The hydraulic conductivity used to compute the streambed conductance is the same conductivity used for modeling subsurface flow. The stream length is the straight-line distance of the stream trace across an individual MODFLOW grid-cell, which was measured using digitized stream maps. The value of Manning's roughness coefficient was chosen based on communications with RFETS Surface Water Division and values listed in Prudic (1988). The remaining values in Table 7-3 were used as listed.

The use of the MODFLOW drain package to simulate subsurface water control features requires the specification of a conductance term and drain elevation for each grid node containing a drain. In the current groundwater flow model there are 117 grid cells designated as drains distributed across two drain systems. The elevation for most of the drain cells was set at or below the bedrock elevation for that cell. Exceptions to this occurred for those drain cells in the northeastern portion of the subsurface drain system, adjacent to the Solar Evaporation Ponds. There is evidence that the drains in this area are located above the top of bedrock (EG&G, 1994a). The elevations for these drains were based on reported information (EG&G, 1994a). The conductance term for the drain cells were adjusted as part of the model calibration. The final conductance values ranged from 0.5 to 5 feet^2/day.

Because the current groundwater flow model only considers the unconsolidated surficial materials, the base of the model was set at the top of bedrock. Top of bedrock elevation information is incorporated into the flow model as a two-dimensional grid of values, one value for each grid node.

The grid of bedrock elevations was produced using the Dynamic Graphics Incorporated (DGI) surface-interpolation software. The original bedrock grid was developed using a 50-foot grid spacing. These data were then re-sampled at the grid spacing used in the groundwater flow model. The data used to develop this grid come from a compilation of 960 data points for bedrock elevation assembled from borehole information. This grid is the same as that used to produce the bedrock elevation map *contained within the Geologic Characterization Report for the Rocky Flats Environmental Technology Site* (EG&G, 1995).

As a starting point for the simulations, an initial groundwater-elevation (head) grid is input to the MODFLOW model. For these simulations, this grid was developed to represent conditions during Spring, 1992.

The groundwater-elevation grid represents average groundwater elevations in alluvial materials for the period between April 1 and May 30, 1992. The data to create this grid were retrieved from RFEDS, and include information from 274 wells, 36 of which were considered to be dry. The groundwater-elevation grid was produced using the DGI surface-interpolation software. The original grid was developed using a 50-foot grid spacing. The data were then re-sampled at the grid spacing used in the groundwater flow model.

7.1.2.1.4 Groundwater Flow Model Boundary Conditions

As part of the mathematical definition of the groundwater flow model, the conditions at the outer boundary of the model grid must be specified. In MODFLOW these boundary conditions are typically either no-flow or constant head. No-flow boundaries are composed of grid cells that are not active in the flow modeling system. Because these cells are not incorporated into the flow system, there is no water flux into or out of this type of cell. Constant head boundaries are composed of grid cells for which the head does not change during the entire simulation. Both of these types of boundaries were used for the flow modeling.

The western and eastern grid margins of the groundwater flow model were set up as constant head boundaries (Figure 7-8). This was done primarily because there was no well-defined physical groundwater flow boundary near these margins. The north and south grid margins were composed of a mixture of no-flow and constant head boundaries. No-flow boundaries were used where a groundwater flow divide was believed to exist. Along regions of the model boundary where a flow divide was not believed to exist, constant head cells were employed. Some constant head and no-flow cells were also used within the interior of the model domain. Constant head cells were used to model relatively large surface water bodies such as the ponds along Woman and Walnut Creek. No-flow cells were used to represent unsaturated areas within the model. The unsaturated areas were assigned using information from the 1993 *Final Well Evaluation Report* (EG&G, 1994b).

7.1.3 Groundwater Flow Model Calibration

The calibration of the groundwater flow model is presented in this section. Included is a description of the techniques used during calibration, and the results of the calibration. A more comprehensive discussion of factors affecting calibration can be found in the 1993 *Sitewide Groundwater Flow Modeling Status Report* (EG&G, 1993c).

Model calibration is the process of adjusting the model input parameters to minimize the difference between the model output and some set of observed data. In the case of the model presented here, the calibration parameters are the hydraulic conductivity, recharge, and drain conductance values; the observed data are water level elevations measured in wells during Spring, 1992.

7.1.3.1 Calibration Process

During the calibration process, various model parameters are adjusted so that the model output (values of head) more closely match the observed data. This is typically an iterative process that involves running the model, evaluating the output, adjusting the input, and running the model again. This was the technique used for this task. The model output was evaluated against the observed data and against the general pattern of head and head change (drawdown) values. In areas with significant calibration errors, the model inputs were adjusted. The hydraulic conductivity, net recharge, and drain conductance values were the model inputs changed during model calibration. One or several of these parameters were adjusted depending on the magnitude of the calibration error and the hydrogeologic setting of the area. Typically during the calibration process, hydraulic conductivity was the first parameter adjusted. In areas where the modeled heads were too high, the conductivity values were increased; in areas where the modeled heads were too low, conductivity values were decreased. If adjustments of the hydraulic conductivity values within the expected ranges were not adequate to improve the calibration, then the values of areal recharge and/or drain conductance were adjusted as appropriate. Recharge values were increased to raise the simulated heads, or decreased to lower the simulated head elevations. Drain conductance terms were increased to lower modeled heads or decreased to raise modeled heads. Because the streambed conductance parameter for the stream-routing package is influenced by the hydraulic conductivity, these terms were recalculated whenever hydraulic conductivity values were altered. The spatial distribution of hydraulic conductivity and recharge values from the final model calibration are presented in Figures 7-9 and 7-10, respectively.

7.1.3.2 Current Calibration Status

The results presented here reflect the current status of the model calibration. The groundwater head distribution resulting from this calibration effort was that used in the subsequent particle tracking study.

MODFLOW computes a volumetric budget to monitor total mass balance during a simulation to determine whether significant mass balance errors are accumulating. The volumetric budget for the groundwater flow model showed a mass balance error (calculated as mass in minus mass out) of negative 3.3 percent over the entire simulation. Mass balance errors on the order of 1 percent are typically considered tolerable (Anderson and Woessner, 1992). Considering the large number of time steps simulated, this amount of mass balance error is considered acceptable.

The observed data for the calibration consisted of average groundwater elevation for the period from April 1, to May 30, 1992 for 138 alluvial monitoring wells located within the study area. This excludes any wells located within desaturated areas. The data for these wells were obtained from the RFEDS.

A map showing Spring, 1992 water elevations contours based on observation well data and the output from the groundwater flow model was constructed to compare the observed and modeled head configurations (Figure 7-11). This map illustrates how the flow model tends to smooth out some of the small-scale irregularities in the map of observation data. Some of this smoothing is due to the coarseness of the grid used in the groundwater flow model. Posted on this map are the values of the residuals (computed as modeled head minus observed head) at each of the monitoring wells. The larger calibration errors tend to occur along the hillsides leading into the major drainages. This is likely due to the large change in gradient and irregular bedrock topograhpy in these areas. The pattern of the simulated head contours and the values of the residuals indicate that the flow model has reached an acceptable level of calibration.

A more detailed analysis of the model calibration is available from investigating the residuals between the observed and modeled groundwater head elevations. Some general statistics computed using the groundwater head residual and the absolute value of the residual are presented in Table 7-4. These values are based on data from the 138 observations (monitoring wells).

A histogram showing the breakdown of the residual absolute values is presented in Figure 7-12. This figure also shows a cumulative frequency curve indicating that approximately 75 percent of the observation points have absolute head residuals of three feet or less. Approximately 35 percent of the observation points have absolute head residuals of one foot or less.

7.2 Particle Tracking

The following discussion presents information regarding the particle tracking model used in the groundwater flow path analysis. The particle tracking code uses the flow field computed by the groundwater flow model to trace the path of particles within the groundwater system. There is no retardation of the particles due to interactions with the solid matrix, so the particles travel at the

Table 7-4
Residual Statistics

	Head Residual (feet)	Absolute Value Of Head Residual (feet)
Mean	0.05	2.15
Standard Deviation	2.96	2.03
Minimum	-11.22	0.00
Maximum	9.12	11.22

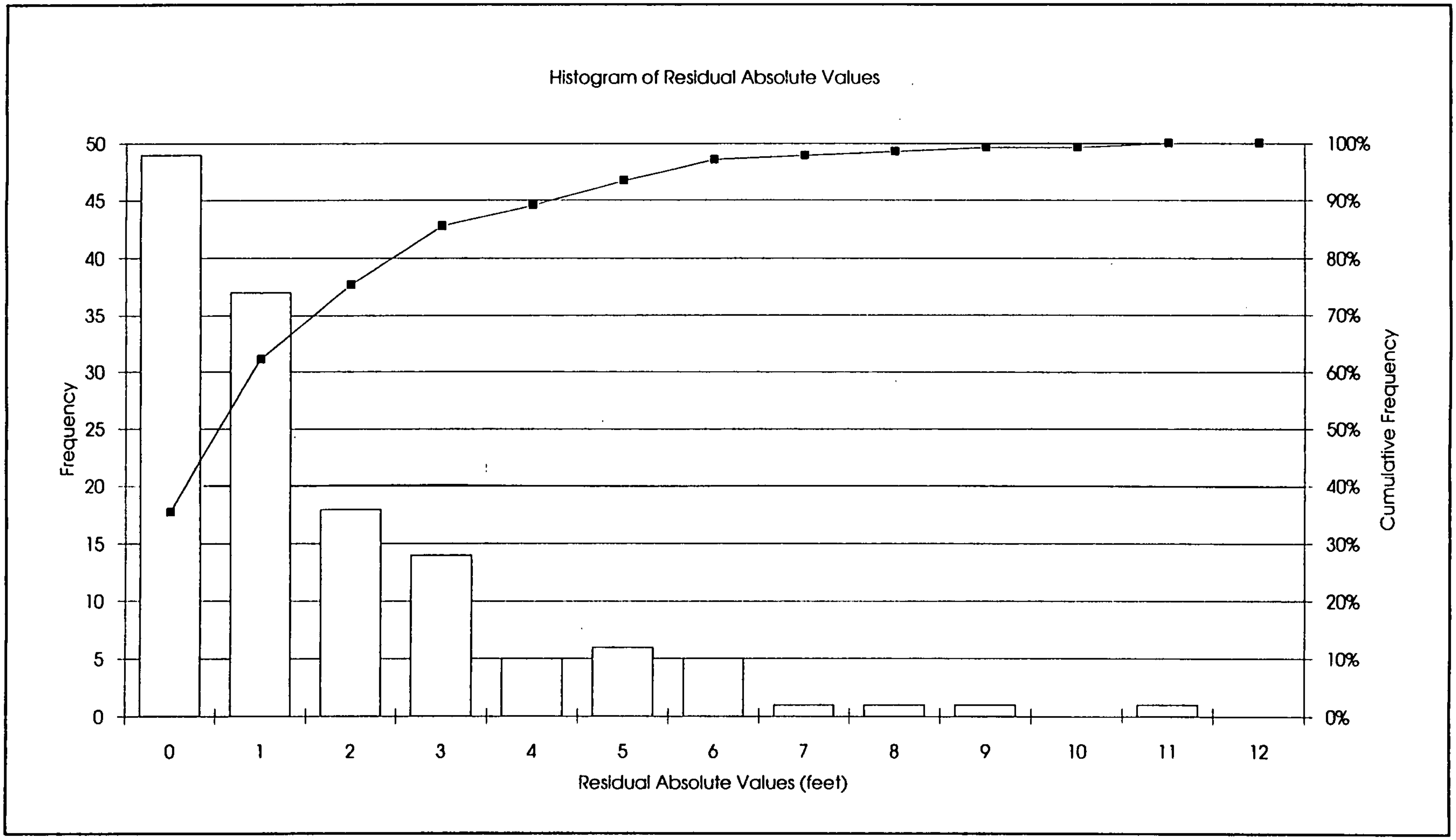


Figure 7-12. Histogram and cumulative frequency curve of absolute value of residuals.

velocity of the groundwater. Any contaminant which is retarded by interacting with the solid matrix would travel at a correspondingly slower velocity, and so would travel a smaller distance than shown by the results presented here.

7.2.1 Mathematical Modeling Code

General aspects of the computer code used for the particle tracking, why this code was selected, and the output generated by the code are discussed in this section. The computer code selected for the particle tracking portion of this project was PATH3D (Zheng, 1989). This code is designed to directly use the output of the MODFLOW groundwater flow model. PATH3D is distributed and supported by S.S. Papadopulos & Associates, Inc. (Bethesda, MD). Below is a discussion of the criteria used in selecting PATH3D for this project.

The main criteria used for selecting the computer code to use for this project were that the selected model should be:

- Able to incorporate key hydrogeologic processes and accurately represent conditions known to occur at the site;
- Able to satisfy the objectives of the study;
- Verified using published equations and solutions;
- Complete and well documented and preferably available in the public domain; and,
- Practical and cost-effective in terms of actual applications as well as resolution of uncertainty.

The PATH3D particle tracking program was selected based on each of the criteria based on the following observations.

- Because PATH3D uses the groundwater flow field computed by the flow model, it does not need to include a means for simulating major hydrogeologic processes. It does include other processes important for particle tracking purposes, including recognition of stagnation zones, and source and sink cells.

- The objective of this portion of the project is to provide particle locations through time as the particle tracking simulation progresses. PATH3D meets this objective by providing this information at the end of each tracking step. This information is supplied in a format which allows it to be easily incorporated into graphical display software.

- Information regarding verification of PATH3D against analytical solutions is presented in Chapter 4 of the program user's manual (Zheng, 1989). The results presented in the manual indicate that PATH3D provides travel time values consistent with those from analytical solutions.

- PATH3D is a complete package for particle tracking which integrates well with the MODFLOW groundwater flow model. PATH3D comes with a comprehensive user's manual and the program's FORTRAN source code. The code is available from the original vendor (S.S. Papadopulos & Associates) or from the IGWMC.

- Several modeling pre-processors and post-processors are available for aiding in PATH3D input data development and output analysis. The PATH3D code is written in standard FORTRAN 77 and can easily be implemented on any computer that has an appropriate compiler. These factors provide for the practical and cost-effective application of this code to the groundwater flow path analysis project. The structure and character of the PATH3D input and output data sets provide sufficient means for standard sensitivity analysis.

PATH3D is a three-dimensional, groundwater flow path and travel-time simulation package. It uses hydraulic conductivity, head distribution, and grid spacing information from a flow model to compute groundwater flux in three dimensions (x, y, z). These fluxes are then used to compute velocities by dividing by a porosity value. Values of flux and velocity are calculated at each grid node in the model assuming a block-centered grid. The velocities are then used in a fourth-order Runge-Kutta tracking scheme to determine the new particle locations for each tracking time step.

The output from PATH3D lists the particle locations at various times during the simulation. In addition, optional output files providing additional information and formats are also available. The initial location of the particles and the total simulation time are specified by the user. The user also specifies how particles are influenced by sink cells in the groundwater flow field and the error criterion for the particle tracking. The values used for these parameters are discussed below.

7.2.2 Particle Tracking Model Implementation

The source code for the PATH3D simulation model was obtained from the original distributor, S.S. Papadopulos & Associates. The source code is also available from the IGWMC.

The FORTRAN source code files were transferred to an IBM RS6000 UNIX workstation for compilation. The PATH3D documentation indicates a change to an input file unit number may be required for compatibility with different implementations of MODFLOW. This change was made and documented in the source code. No errors were encountered during compilation of the source code.

After installation and compilation of the source code, the executable model was benchmarked against example files provided by the software vendor. The results from the benchmarking indicate there are no significant differences between the vendor-supplied executable and the recompiled version of the code. The details of this process are provided in Appendix E.

7.2.3 Data Used in the Particle Tracking Model

As discussed above, PATH3D obtains the groundwater flow field information needed for the particle tracking using the results from a groundwater flow model such as MODFLOW. One of the primary pieces of information obtained from the groundwater flow model is the groundwater head data file. This file gives the head distribution information (in this case the elevation of the groundwater table) for the study area. The head data file used in this study represents the final head distribution from the MODFLOW simulations.

PATH3D acquires additional information required for the particle tracking by reading in the MODFLOW input files used for the groundwater flow simulation. These files contain information such as grid-node spacing, hydraulic conductivities, and the locations of drain and stream nodes.

As part of the vertical (z) dimension tracking process, PATH3D requires top elevation and thickness of each layer in the groundwater flow model. For this single layer model the top elevation was taken as the topographic elevation for each grid node. The thickness of each grid cell was input as the difference between the topographic and bedrock elevations at each grid node.

A value for effective porosity is needed for the velocity calculations within PATH3D. The standard particle tracking results presented here used a value of 0.10 for effective porosity. This is the same value used for specific yield in the MODFLOW groundwater flow model. Information regarding the choice of this value is given in Section 7.1.2.1.3, which describes the MODFLOW flow model.

In PATH3D the initial locations for the particles are designated by the user. Particles may be placed virtually anywhere within the model domain. For this study, the initial particle locations were always placed at points corresponding to grid node locations from the groundwater flow model. The contaminant distribution maps from the 1993 *Well Evaluation Report* (EG&G, 1994b) were used to determine which grid nodes locations would be used as particle starting points. The outermost concentration contour for each contaminant used in the particle tracking was used to define the boundary for the initial particle locations. A single particle was tracked starting from each grid node within this boundary.

As particles are tracked across the study area they may enter grid cells which would be considered sink (groundwater discharge) cells in the groundwater flow model. Grid cells which contain wells, drains, or stream nodes in the flow model can be sink cells. Although these cells may act as sinks in the groundwater flow model, if the cell is relatively large or if the inward flow rate at each edge of the cell is not sufficiently large, then particles may be tracked out of these cells (Zheng, 1989). To address this concern, PATH3D has several options on how to address particles that enter sink cells. The technique used in this study only removes particles at sink cells which have an inward gradient along each face of the grid cell. This solution has the advantage of allowing particles to stay within the groundwater flow system until a true sink cell, as indicated by the groundwater flow model, is encountered. The disadvantage to this technique is that sink cells which are relatively weak in the flow model may allow particles to pass through them, which may not accurately reflect the physical system.

The particle tracking results presented here represent 10 years (3,650 days) of particle transport. This time interval was chosen to allow sufficient time for tracking groundwater migration, and yet provide results meaningful for selecting onsite monitoring well locations. The groundwater flow field from the final time step of the MODFLOW simulation was used during the entire particle tracking simulation. PATH3D adjusts the tracking time step length during the simulation to achieve a prescribed error criterion. The initial time step was set at 10 days. The model-adjusted time step varied from less than one day to over 100 days.

7.2.4 Groundwater Flow Path Analysis

To make a general assessment of the existing monitoring well network at RFETS, the particle tracking methodology described above was applied to contaminant distribution information for several individual contaminants. The individual contaminants used in the particle tracking are listed in Table 7-5.

In addition to these individual contaminants, a composite map assembled from individual composite maps contained within the 1993 WER (EG&G, 1994b) was used to define particle starting locations for one of the simulations. The individual composite maps used to generate this comprehensive composite are listed Table 7-6. The details of contaminant distribution maps development are contained in the 1993 WER (EG&G, 1994b).

7.2.5 Particle Tracking Results

Results from the groundwater flow path analysis is presented in this section and some general discussion are included regarding possible improvements in the existing monitoring well network. These improvements involve the installation of additional monitoring wells. The locations for these wells are based on the results from one or more of the pathway analyses and are consistent with the

Table 7-5
Individual Contaminant Distributions Used In Particle Tracking

Contaminant	Monitoring Period Represented	1993 WER* Plate
Americium-241	2nd Quarter 1992	2-67
Average** Tetrachloroethene	Jan. 1989 to Mar. 1993	2-89
Average** Total Dissolved Solids	Jan. 1989 to Mar. 1993	2-107
Nitrate plus Nitrite	2nd Quarter 1992	2-113

*Source: EG&G, 1994b
**Average of monitoring period represented

Table 7-6
Individual Composite Maps Used To Generate Comprehensive Composite Map

Contaminant	1993 WER* Plate
TDS, SO_4, NO_3 + NO_2	2-125
Selenium	2-126
TCE, PCE, VOC	2-127
Gross Alpha, Gross Beta, Uranium, Lithium	2-113

*Source: EG&G, 1994b

general locations suggested in the 1993 WER (EG&G, 1994b). The locations of these additional wells are approximate; the actual field location should be determined using site specific information.

A location map giving place names discussed in the text is provided in Figure 7-13. The particle tracking results are presented in Figures 7-14 through 7-18. In these figures, the contaminant extent boundaries from the 1993 WER (EG&G, 1994b) are shown by red polygons. The small + symbols within these polygons represent the locations of the groundwater flow model grid nodes used as the initial locations for the particles. The model does not track particles from grid nodes located within unsaturated regions since these are no-flow regions in the flow model.

In these figures, different colors are used to designate the character of the different particle traces. An orange particle trace indicates the complete 10 year path of a particle which at the end of 10 years was still in the groundwater flow system. A blue-green particle trace indicates that the particle entered a surface water stream before the end of the 10-year tracking period. A green particle trace indicates that the particle was trapped by a drain cell or some other cell with an inward gradient and was exceeded before the complete 10-year path could be traced. This typically occurs where there are large changes in the groundwater velocity. The maximum number of tracking steps for any given particle is designated as part of the model input. For the simulations presented here a maximum value of 1,000 time steps was used. Increasing this value did not significantly change the number of particles which reached this limit. A particle which exceeds the number of tracking time steps typically is using an extremely small time step (1/1,000 day) when the limit is reached.

The locations of alluvial groundwater monitoring wells, surface water features, roads and buildings, subsurface drains included in the groundwater flow model, the extent of the Rocky Flats Alluvium, and the location of desaturated areas are also shown on the maps. The location of the 881 Hillside (OU1) French Drain is also shown. This subsurface drain was not included in the groundwater flow model for reasons discussed above. Its location is provided as a reference in interpreting the results from the particle tracking.

While examining the results from this particle tracking exercise several key points should be understood:

- The particle traces represent the distance groundwater would flow in 10 years, a contaminant which is retarded would travel at a much slower rate;
- Results from smaller scale (Operable Unit level) models may differ from those presented here because of differences in modeling scales and grid spacing;
- The resolution of the particle tracking results is, in part, dependent on the grid spacing of the underlying groundwater flow model;
- The particles are tracked for a period of 10 years using a groundwater flow field which represents wetter-than-normal conditions at RFETS;
- The 881 Hillside French Drain was not included in the groundwater flow model, therefore particles appear to track across it. It is believed that all the particle traces that impinge upon the French Drain would, in reality, be captured by the drain. In addition, because of the drain's influence on the groundwater flow field, many of the particle traces near the ends of the drain would also be captured; and,
- The foundation drain systems for the buildings are not included in the model. Because of the limited range of influence of those drains relative to the scale of this modeling project, it is believed that their effect on the groundwater flow system would not have significantly changed the suggested monitoring locations presented here.

7.2.5.1 Nitrate Plus Nitrite Results

The results from the particle tracking for the nitrate plus nitrite contaminant boundaries are presented in Figure 7-14. The particle tracking results presented in this figure indicate that the current monitoring network is fairly well situated to sample the groundwater pathways originating from these contaminated regions. Additional monitoring should be considered in the areas indicated on the map. In particular, the pathline originating in the East Trenches (OU2) which traces south towards Woman Creek indicates a need for additional monitoring.

7.2.5.2 Americium-241 Results

The results from the particle tracking for the americium-241 contaminant boundaries are presented in Figure 7-15. The particle tracking results presented in this figure indicate that the current monitoring network is fairly well situated to sample the groundwater pathways originating from these contaminated regions. Two additional monitoring locations are suggested. One area is along the middle reach of the North Walnut Creek Drainage; the other is to the southeast of the 903 Pad.

7.2.5.3 Tetrachloroethene Results

The results from the particle tracking for the tetrachloroethene contaminant boundaries are presented in Figure 7-16. The particle tracking results presented in this figure indicate that the current monitoring network is fairly well situated to sample the groundwater pathways originating from a majority of these contaminated regions. Several areas for additional monitoring are suggested. These include locations within the Walnut and Woman Creek drainages and a location to the east of the East Trenches.

7.2.5.4 Total Dissolved Solids Results

The particle tracking results for the TDS contaminant boundaries are presented in Figure 7-17. These results indicate that additional monitoring wells may be needed in the regions indicated on the map. A major area of concern is the Walnut Creek Drainage.

7.2.5.5 Composite Contaminant Extent Results

The results from the particle tracking for the composite contaminant boundaries are presented in Figure 7-18. For this particular groundwater flow path analysis, particles were only tracked from the outer limit of the contaminant boundary. This reduces the number of pathlines to provide a clearer representation of the groundwater flow paths at the outer reaches of the contaminant boundary. Because this map is a composite of different maps, several other areas which might require additional monitoring are shown. In particular, the trace lines originating near the Present Landfill and ending near the North Walnut Creek Drainage indicate additional monitoring requirements in this area. Further monitoring also is suggested for the southern slope of the South Walnut Creek Drainage, based on pathlines originating in the north-eastern corner of the East Trenches.

8.0 SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

- Review of RFETS drilling and well construction procedures, and of the literature in the groundwater industry, suggests that isolation of surface soils from screened intervals should be a required procedure at RFETS. The results of the review indicate that drilling methods are less critical to controlling cross contamination than is the isolation of known or suspected zones of contamination in a borehole from other portions of the borehole.

- The typical fine-grained nature and low productivity of the saturated zones in the sediments at RFETS suggest that sediment accumulation in wells cannot be completely alleviated. The most effective means of minimizing the impact of sediments to the water chemistry of groundwater samples is to optimize well construction by using appropriate well screen and sandpack designs, by continuing the current practice of developing wells using low energy techniques, and by adopting low flow sampling methods.

- The field evaluation demonstrated that multiparameter instruments for measuring field parameters will equal or exceed the performance of the instrumentation currently used in RFETS groundwater monitoring program. The most consistently reliable turbidity data was collected by the Hach 2100P turbidimeter. The Hach 2100P is not adaptable to flow cells. Of the multiparameter instruments, the Hydrolab H20 provided somewhat more reliable field parameter data.

- Flow cells were shown to be an improvement from the current method of monitoring field parameters in that no handling or transfer of the purge or sample water is necessary. This results in less sample turbulence and little to no air contact. Consequently, the data quality of both the field measurements and the laboratory analytical results are likely to be enhanced. The use of flow cells allows real-time monitoring and recording of data, enhancing the reliability and consistency of the field measurements. Flow cells require the use of downhole pumping systems.

- The field evaluation also demonstrated that low flow purging and sampling is an effective and improved method over the current RFETS method of bailing wells. Wells that historically produced turbidity at greater than 1,000 NTU using bailers to purge and collect samples produced values below 5 NTU using the low flow method. Once experience in using the pumps was gained by the field crews, purge volumes to attain field parameter stability were generally less than one gallon, contrasted to the three well volume purging of five to six gallons required with bailers. Minimizing the volume of purge water is an important benefit of the method.

- The electric submersible Grundfos pump is not considered suitable for low flow purging and sampling at RFETS because of the typically low yield wells onsite. In addition, the sensitivity of the Grundfos controller to water and moisture is a concern over extended periods of daily use. All bladder pumps performed well, though given the typically short standing water columns in wells at RFETS, the Marschalk and Isco pumps are recommended because of their enhanced low-submergence pumping capabilities.

- All wells at RFETS are candidates for dedicated pump systems. Even wells that produce water at such low rates that times for purging and sampling would be prohibitively long are amenable to the method. Those wells can be purged and dewatered, then sampled the following day with low flow pumping rates (50 to 150 ml/min). Though even such low flow rates may exceed the recovery rate of a well, they are warranted because low turbidities will be maintained and because field parameters can be measured in flow cells.

- A statistical analysis using the Student's t-test indicates that, at a 95 percent confidence level, there is no statistical difference in concentrations of metals and radionuclides between filtered and unfiltered samples collected using the low flow method. The results of the statistical analysis further suggest that there is generally also no difference in radionuclide concentrations between filtered bailed and filtered low flow pumped samples. Conversely, the analysis suggested that there is a difference between the unfiltered bailed and unfiltered low flow pumped samples. The field evaluation also demonstrated that analytical results showed little difference between unfiltered low flow pumped samples and filtered bailed samples. These results indicate that, based on the four well evaluation, turbidity has a significant impact on metals and radionuclide concentrations in samples collected from RFETS monitoring wells.

- The overall conclusion that can be drawn on the results of the statistical analysis is that samples collected using the low flow purging and sampling methods may not need to be filtered. Significant savings in laboratory costs can be realized by analyzing only unfiltered samples. Furthermore, smaller sample volumes would be collected and more wells could be sampled the same day they are purged. Because of the shorter time period between purging and sampling, the samples collected potentially would be more representative of groundwater chemistry at RFETS.

- Groundwater flow modeling was conducted to provide a basis to locate future site protection monitoring wells at RFETS. A 10-year simulation was conducted. The results of the analysis indicated 13 locations for potential additional monitoring wells.

9.0 REFERENCES

APHA, 1992. *4500-0 Oxygen (Dissolved)*. American Public Health Association. Environmental Monitoring Methods Index, Version 1.0. 821-B-92-001. US Environmental Protection Agency. Washington, D.C.

ASTM, 1992. *Standard Test Method for Dissolved Oxygen in Water*. D888. ASTM.11.01. American Society for Testing and Materials. Philadelphia, PA. Environmental Monitoring Methods Index, Version 1.0. 821-B-92-001. US Environmental Protection Agency. Washington, D.C.

ASTM, 1994. *Standard Test Method for Turbidity of Water*. Standard-D1889. American Society for Testing and Materials. Philadelphia, PA.

Aller, Linda, T.W. Bennett, G. Hackett, R.J. Petty, J.H. Lehr, H. Sedoris, D.M. Nielsen, and J.E. Denne, 1990. *Handbook of Suggested Practices for the Design and Installation of Groundwater Monitoring Wells*. EPA/EMSL-Las Vegas, USEPA Cooperative Agreement CR-812350-01, EPA/600/4-89/034. US Environmental Protection Agency, Las Vegas, NV.

Anderson, Mary P., and Woessner, William W., 1992. *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*. Academic Press, Inc. San Diego, CA.

Anderson, P.F., 1993. *A Manual of Instructional Problems for the U.S.G.S. MODFLOW Model*. US Environmental Protection Agency. Robert S. Kerr Environmental Research Laboratory, Ada, OK.

Ault, T.D., S. Logan, and A.J. Madaj, 1994. *Rotary Sonic Drilling for Environmental Investigation - Applications to Stratigraphic Characterization and Correlation*. National Outdoor Action Conference and Exposition Proceedings. National Ground Water Association. Minneapolis, MN. May.

Bangsund, William J., C.G. Peng, and Wayne R. Mattsfield, 1994. *Investigation of Contaminant Migration by Low-Flow Rate Sampling Techniques*. National Outdoor Action Conference and Exposition Proceedings. National Groundwater Association. Minneapolis, MN. May.

Barcelona, Michael J., H. Allen Wehrmann, and Mark D. Varljen, 1994. *Reproducible Well-Purging Procedures and VOC Stabilization Criteria for Ground-Water Sampling*. Ground Water. Vol. 32, No.1. January-February.

Barrow, Jeffrey C., 1994. *The Resonant Sonic Drilling Method: An Innovative Technology for Environmental Restoration Programs*. Ground Water Monitoring and Remediation. Vol. 14, No. 2. Spring.

Boyle, D.R., 1992. *A Dry Injection System for the Emplacement of Filter Packs and Annular Seals in Ground Water Monitoring Wells*. Ground Water Monitoring Review. Vol 12, No. 1. Winter.

Clark, Sue B., Natalie M. Park, and R. Cary Tuckfield, 1992. *Effects of Sample Collection Device and Filter Pore Size on Concentrations of Metals in Groundwater Samples*. National Groundwater Sampling Symposium Proceedings. Washington, D.C. November.

Colorado, 1993a. *Colorado Regulations Pertaining to Solid Waste Disposal Sites and Facilities. 6 CCR 1007-2. Appendix II for Assessment Monitoring*. Effective from October 9th 1993. Denver, CO.

Colorado, 1993b. *State of Colorado Procedural Rules, Section 2.1.3, "Classification and Water Quality Standards for Ground Water", 3.12.0 (5 CCR 1002-8)*. Amendment of 27th December 1993. Denver, CO.

Drever, Jones I., 1988. *The Geochemistry of Natural Waters*. 2nd Edition. Prentice Hall, Inc. Englewood Cliffs, NJ

Driscoll, Fletcher G., principal author and editor, 1986. *Groundwater and Wells*, 2nd Edition. Johnson Division, St. Paul, MN.

EG&G, 1991. *Well Evaluation Report*. EG&G-Rocky Flats, Inc. Golden, CO. November.

EG&G, 1992a. *Background Geochemical Characterization Report*. EG&G-Rocky Flats, Inc. Golden, CO. September.

EG&G, 1992b. *Final Phase II RFI/RI Aquifer Test Report, Volume I - Text, 903 Pad, Mound, and East Trenches Areas (Operable Unit No. 2)*. EG&G-Rocky Flats, Inc. Golden, CO. November.

EG&G, 1993a. *Final Phase III RFI/RI, Rocky Flats Plant 881 Hillside Area (Operable Unit No. 1), Volume VI, Appendix B, Hydrogeologic Data*. EG&G-Rocky Flats, Inc. Golden, CO. September.

EG&G, 1993b. *Groundwater Protection and Monitoring Program Plan*. EG&G-Rocky Flats, Inc. Golden, CO. October.

EG&G, 1993c. *Status Report: Site-wide Groundwater Flow Modeling at the Rocky Flats Plant, Golden, Colorado*. EG&G-Rocky Flats, Inc. Golden, CO. November.

EG&G, 1993d. *Groundwater Geochemistry of Rocky Flats Plant*. EG&G-Rocky Flats, Inc. Golden, CO. December.

EG&G, 1994a. *OU4 Solar Evaporation Pond Interim Measures/Interim Remedial Action*

Environmental Assessment Decision Document, Roundtable Review Draft Revision, Rocky Flats Plant, Golden, Colorado. EG&G-Rocky Flats, Inc. Golden, CO. February.

EG&G, 1994b. *Final Well Evaluation Report, Rocky Flats Plant, Golden, Colorado*. EG&G-Rocky Flats, Inc. Golden, CO. April.

EG&G, 1994c. *Groundwater Protection and Monitoring Program Plan, Draft Final*. EG&G-Rocky Flats, Inc. Golden, CO. September.

EG&G, 1994d. *Environmental Management Department Operating Procedures Manual, Volume I: Field Operations (Manual No. 5-21000-OPS-FO), Volume II: Groundwater (Manual No. 5-21000-OPS-GW), and Volume III: Geotechnical (Manual No. 5-21000-OPS-GT)*. EG&G-Rocky Flats, Inc. Golden, CO.

EG&G, 1995. *Geologic Characterization Report for the Rocky Flats Environmental Technology Site*, Final Report. March.

EPA, 1983. *Methods for Chemical Analysis of Water and Wastes*. EMSL-Ci, EPA/600/4-79-020. US Environmental Protection Agency. Washington, D.C. March.

EPA, 1986a. *RCRA Ground-water Monitoring Technical Enforcement Guidance Document*. OSWER-9950.1. US Environmental Protection Agency. Washington, D.C.

EPA, 1986b. *Test Methods for Evaluating Solid Waste*. SW-846. 3rd Edition. US Environmental Protection Agency. Washington, D.C.

EPA, 1989. *Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities. Interim Final Guidance*. US Environmental Protection Agency. Washington, D.C. April.

EPA, 1991. *Summary of Final Draft of Chapter 11 of SW-846, "Ground-Water Monitoring"*. US Environmental Protection Agency. Washington, D.C. October.

EPA, 1992a. *Highlights, Acquisition of Ground-Water Quality Samples for Metals, Status Report for 2/17/92*. US Environmental Protection Agency. Robert S. Kerr Environmental Research Laboratory, Ada, OK. February.

EPA, 1992b. *RCRA Ground-Water Monitoring: Draft Technical Guidance*. EPA/530-R-93-001. US Environmental Protection Agency. Washington, D.C. November.

EPA, 1992c. *Environmental Monitoring Methods Index*. Version 1.0. US Environmental Protection Agency. Washington, D.C. January.

EPA, 1994a. *Standard Operating Procedure for Well Development*. SOP # 3.2, Region VIII Guidance, Revision 0. Denver, CO. June.

EPA, 1994b. *Standard Operating Procedure for Well Purging*. SOP # 4.1, Region VIII Guidance, Revision 0. Denver, CO. June.

Fedors, R., and J.W. Warner, 1993. *Characterization of Physical and Hydraulic Properties of Surficial Materials and Groundwater/surface water Interaction Study at Rocky Flats Plant, Golden, Colorado*. Colorado State University, Department of Civil Engineering, Groundwater Technical Report #21. Fort Collins, CO.

FERMC, 1993. *Waste Minimization and Groundwater Sampling Efficiency: A New Technique for Purging Groundwater Monitoring Wells at the Fernald Environmental Management Project*. US Department of Energy. Fernald Environmental Restoration Management Corporation. Fernald, OH. October.

Fetter, C.W., Jr., 1980. *Applied Hydrogeology*. Charles E. Merrill Publishing, Columbus, OH.

Garner, Stuart, 1988. *Making the Most of Field-Measurable Ground Water Quality Parameters*. Publ. No. 3043-688. Hydrolab Corporation. Austin, TX.

Gass, Tyler E., James F. Barker, R. Dickhout, and J.S. Fyfe, 1991. *Test Results of the Grundfos Ground-Water Sampling Pump*. National Symposium on Aquifer Restoration and Ground Water Monitoring Proceedings, National Water Well Association.

Gibbons, R.D., 1994. *Statistical Methods for Ground-Water Monitoring*. John Wiley & Sons. New York, NY.

Goof, Sue, 1994. Personal Communication. Los Alamos, NM. July.

Greacen, James, and Kristen Silvia, 1994. *A Comparison of Low Flow vs. High Flow Sampling Methodologies on Groundwater Metals Concentrations*. National Outdoor Action Conference and Exposition Proceedings. National Groundwater Association. Minneapolis, MN. May.

Greenberg, Arnold E., Lenore S. Clesceri, and Andrew D. Eaton, Eds., 1992. *Standard Methods for the Examination of Water and Wastewater*. 18th Edition. American Public Health Association, American Water Works Association, and Water Environment Federation.

Hach, Clifford C., Richard D. Vanous, and John M. Heer, 1990. *Understanding Turbidity Measurement*. Technical Information Series Booklet No. 11. 1st Edition. Hach Company, Loveland, CO.

Hach, Clifford C., 1992. *Turbidity Standards*. Technical Information Series Booklet No. 12. Hach Company, Loveland, CO.

Herzog, Beverly L., Sheng-Fu J. Chou, John R. Valkenburg, and Robert A. Griffin, 1988. *Changes in Volatile Organic Chemical Concentrations After Purging Slowly Recovering Wells*. Ground Water Monitoring Review. Vol. 8, No. 4. Fall.

Hill, Mary C., 1990. *Preconditioned Conjugate-Gradient 2 (PCG2), A Computer Program for Solving Ground-Water Flow Equations*. USGS Water-Resources Investigations Report 90-4048.

Hurr, R.T., 1976. *Hydrology of a Nuclear-processing Plant Site, Rocky Flats, Jefferson County, Colorado*. USGS Open-File Report 76-268.

ISO, 1990. *Water Quality- Determination of Turbidity*. ISO 7027. International Organization for Standardization. Geneva, Switzerland.

Julian, Henry E., and Steven C. Young, undated. *Measuring Well Development with an Electromagnetic Borehole Flowmeter*. Tennessee Valley Authority Engineering Laboratory, Norris, TN.

Kearl, Peter M., Nic E. Korte, and Tom A. Cronk, 1992. *Suggested Modifications to Ground Water Sampling Procedures Based on Observations from the Colloidal Borescope*. Ground Water Monitoring and Remediation. Vol. 12, No. 2. Spring.

Kearl, Peter M., Nic E. Korte, Joe Baker, and Mike Stites, 1993. *Field Comparison of Micropurging versus Traditional Groundwater Sampling*. Environmental Remediation Conference. Augusta, GA. October.

Liang, L., J.F. McCarthy, L.W. Jolley, J.A. McNabb, and T.L. Mehlhorn, 1993. *Iron Dynamics: Transformation of Fe(II)/Fe(III) during Injection of Natural Organic Matter in a Sandy Aquifer*. Geochemica et Cosomochimica Acta. Vol. 57, No. 9. May.

NIOSH, 1990. *Pocket Guide to Chemical Hazards*. US Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health. Washington D.C.

McDonald, Michael G., Harbaugh, Arlen W., Orr, Brennon R., and Ackerman, Daniel J., 1991, *A Method of Converting No-Flow Cells to Variable-Head Cells for the U.S. Geological Survey Modular Finite-Difference Ground-water Flow Model*. USGS Open-File Report 91-536.

McDonald, M.G. and Harbaugh, A.W., 1988. *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*. USGS Techniques of Water Resources Investigations, Book 6, Chapter A1.

Olie, J.J., C.C.D.F. Van Ref, and C. Bremmer, 1992. *In Situ Measurement by Chemprobe of Groundwater from In Situ Sanitation of a Versatic Acid Spill*. Geotechnique. Vol. 42, No. 1. March.

Parker, Louise V., 1994. *The Effects of Ground Water Sampling Devices on Water Quality: A Literature Review*. Ground Water Monitoring and Remediation. Vol. 14, No. 2. Spring.

Parker, Timothy K., Mark F. Eisen, Andrew A. Kopania, Alix Robertson, Rick L. Eades, and Glenn Thomas, 1992. *Selection, Design, Installation, and Evaluation of Dedicated Groundwater Sampling Systems: A Case Study*. National Groundwater Sampling Symposium Proceedings. Washington, D.C. November.

Paul, Cynthia J., and Robert W. Puls, 1992. *Comparison of Ground-Water Sampling Devices Based on Equilibration of Water Quality Indicator Parameters*. National Groundwater Sampling Symposium Proceedings. Washington, D.C. November.

Plato, Paul R., 1993. *SHYDG.FOR - Hydrograph Package for MODFLOW*. Ground Water. Vol. 31, No. 6.

Prudic, David E., 1988. *Documentation of a Computer Program to Simulate Stream-Aquifer Relations using a Modular, Finite-Difference, Ground-Water Flow Model*. USGS Open-File Report 88-729.

Puls, Robert W., Don A. Clark, Bert Bledsoe, Robert M. Powell, and Cynthia J. Paul, 1992. *Metals in Ground Water: Sampling Artifacts and Reproducibility*. US Environmental Protection Agency, Robert S. Kerr Environmental Research Laboratory. Ada, OK.

Puls, Robert W., and Robert M. Powell, 1992. *Acquisition of Representative Ground Water Quality Samples for Metals*. Ground Water Monitoring Review. Vol. 12, No. 3. Summer.

Puls, Robert W., 1994a. *A New Approach to Purging Monitoring Wells*. Ground Water Age. January.

Puls, Robert W., 1994b. *Collecting Representative Ground Water Samples: Field Practices and Procedures. National Outdoor Action Conference and Exposition*. Minneapolis, MN. May.

Robin, M.J.L., and R.W. Gillham, 1987. Field Evaluation of Well Purging Procedures. Ground Water Monitoring Review. Vol. 7, No. 4. Fall 1987.

Ronen, D., M. Magaritz, U. Weber, and A.J. Amiel, 1992. *Characterization of Suspended Particles Collected in Groundwater Under Natural Flow Conditions*. Water Resources Research. Vol. 28, No. 5. May.

Rose, Seth, and Long, Austin, 1988. *Monitoring Dissolved Oxygen in Ground Water: Some Basic Considerations*. Ground Water Monitoring Review. Vol. 8, No. 1. Winter.

Shear, D.L., 1990. *Monitoring Well Design Criteria for the Rocky Flats Alluvium and Five Sandstone Channels*. Internal Document, EG&G-Rocky Flats, Inc. Environmental Monitoring and Assessment. Golden, CO. June.

Spair, J.A., (undated). *The A-B-C's of NTU's: A Primer on Turbidity*. Advanced Polymer Systems. Redwood City, CA.

van der Heijde, Paul K.M., Aly I. Ei-Kadi, and Stan A. Williams, 1988. *Groundwater Modeling: An Overview and Status Report*. International Ground Water Modeling Center, Colorado School of Mines. Golden, CO.

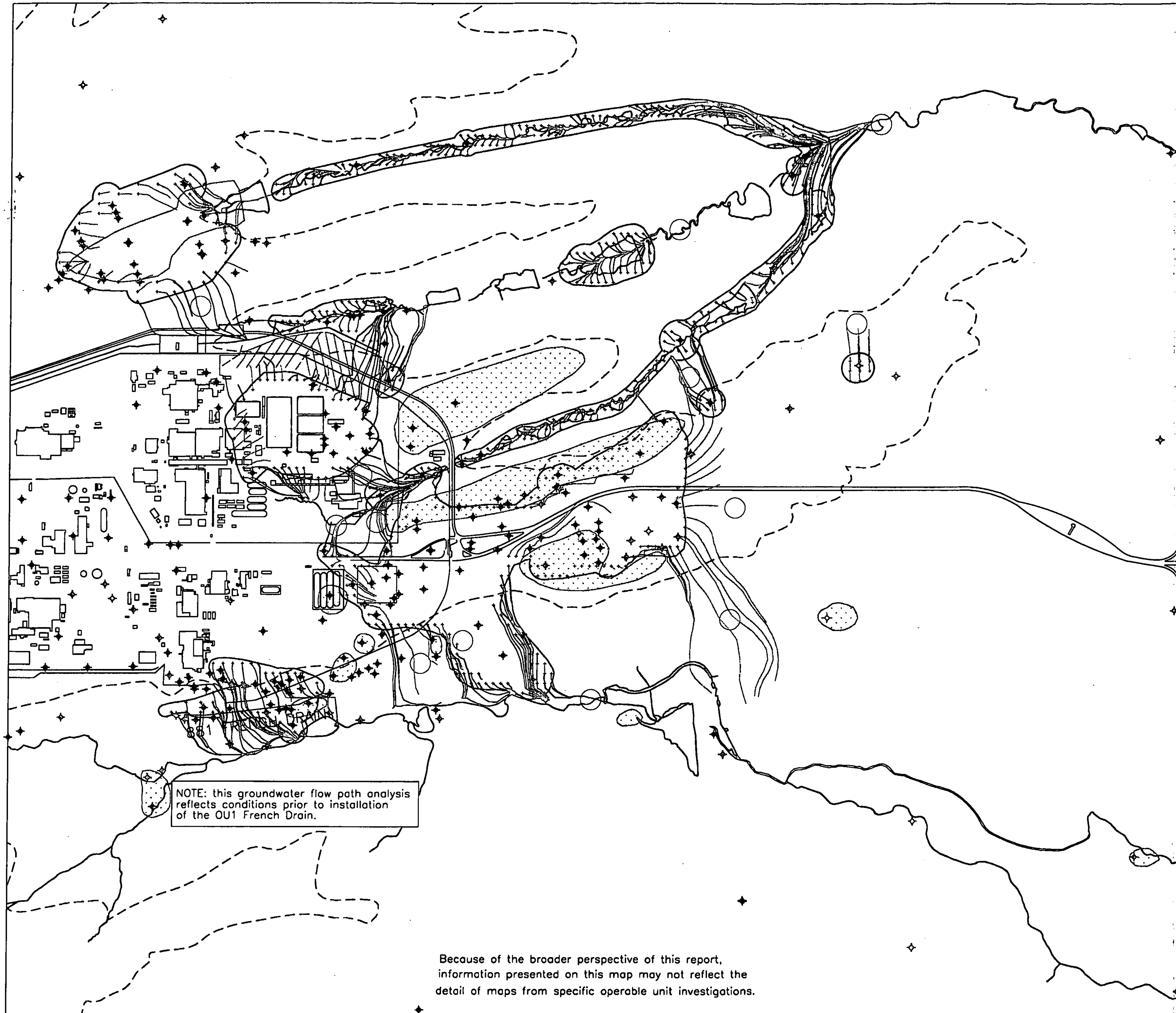
Walton-Day, Katherine, Donald L. Macalady, Myron H. Brooks, and Vernon T. Tate, 1990. *Field Methods for Measurement of Ground Water Redox Chemical Parameters*. Ground Water Monitoring Review. Vol. 10, No. 4. Fall.

White, Art F., Maria L. Peterson, and Ray D. Solbau, 1990. *Measurement and Interpretation of Low Levels of Dissolved Oxygen in Ground Water*. Ground Water. Vol. 28, No. 4. July-August.

Wright, Peter R., and William L. Cunningham, 1994. *Use of Rotatsonic Drilling for Field Investigations of Ground Water at Wright-Patterson Air Force Base, Ohio*. National Outdoor Action Conference and Exposition. National Ground Water Association. Minneapolis, MN. May.

WWE, 1993. *Permitting of Monitoring Wells at the Rocky Flats Plant*. Wright Water Engineers, Inc. Denver, CO. October.

Zheng, Chumiao, 1989. *PATH3D: A Ground-water Path and Travel-time Simulator*. S.S. Papadopulos & Associates, Inc. Bethesda, MD.



U.S. Department of Energy
Rocky Flats
Environmental Technology Site

Composite Contaminant Extent

GROUNDWATER TRACKING PARTICLE TRACE LEGEND

- Contamination Extent From 1993 Well Evaluation Report
- Complete 10 Year Particle Track
- Final Particle Position in Stream at or Before 10 Years
- Particle Captured by Drain or Trapped at Cell at or Before 10 Years
- Number of Tracking Steps Exceeded
- Possible Future Monitoring Site

ALL RESULTS REPRESENT UNRETARDED GROUNDWATER FLOW

- Existing Alluvial Monitoring Well
- Surface Water Feature
- Subsurface Drain
- Extent of Rocky Flats Alluvium
- Unsaturated Area

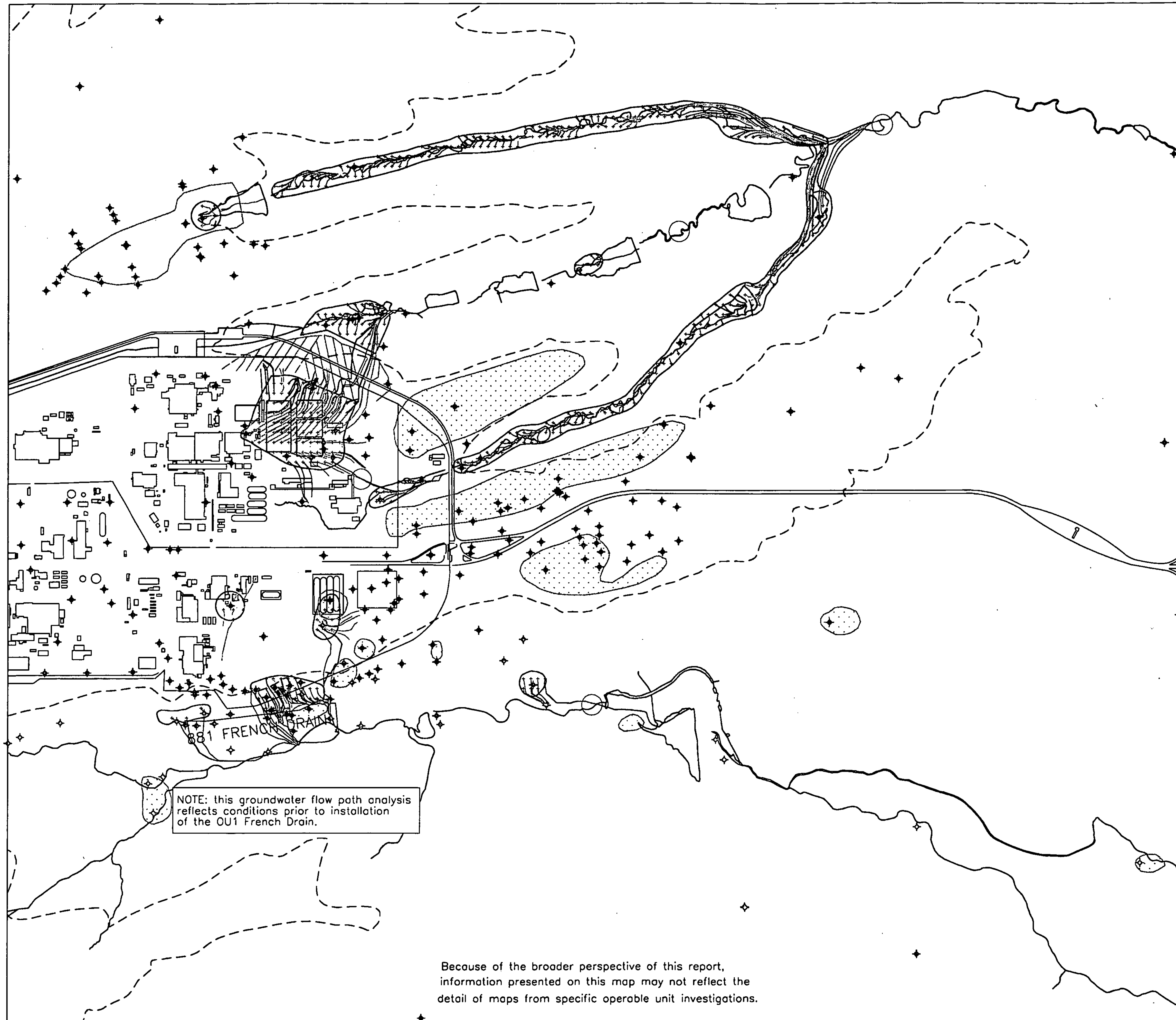
TN
0° 11'

500 0 1000 2000
FEET

State Plane Coordinate Projection

1994 Well Evaluation Report
Figure 7-18

Date: March 1995



U.S. Department of Energy

Rocky Flats

Environmental Technology Site

Average Total Dissolved Solids

GROUNDWATER TRACKING PARTICLE TRACE LEGEND

Contamination Extent From 1993 Well Evaluation Report

Complete 10 Year Particle Track

Final Particle Position in Stream at or Before 10 Years

Particle Captured by Drain or Trapped at Cell at or Before 10 Years

Number of Tracking Steps Exceeded

Possible Future Monitoring Site

ALL RESULTS REPRESENT UNRETARDED GROUNDWATER FLOW

Existing Alluvial Monitoring Well

Surface Water Feature

Subsurface Drain

Extent of Rocky Flats Alluvium

Unsaturated Area

TN

0° 11'

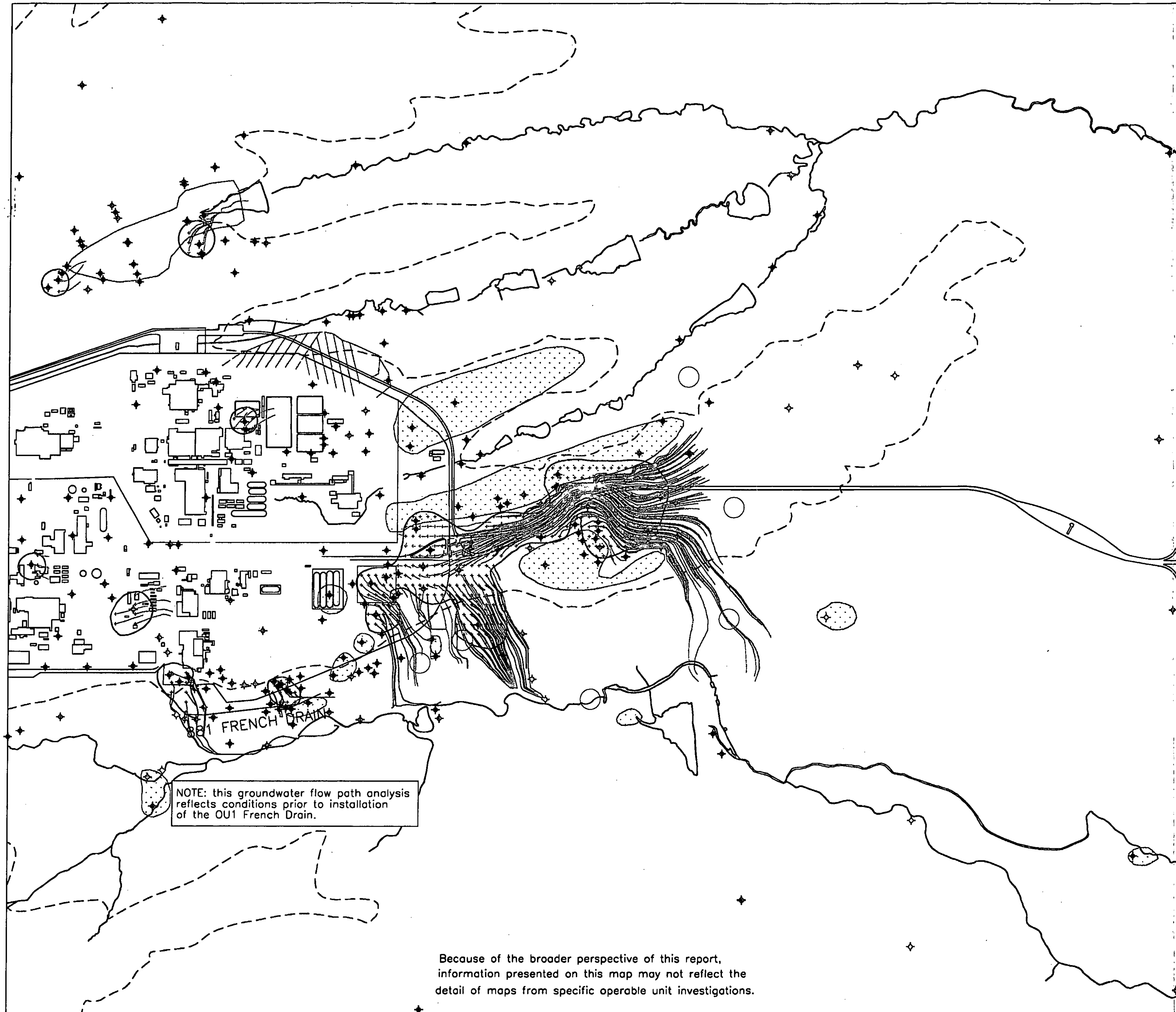
500 0 1000 2000

FEET

State Plane Coordinate Projection

1994 Well Evaluation Report
Figure 7-17

Date: March 1995



U.S. Department of Energy
Rocky Flats
Environmental Technology Site

Average Tetrachloroethene Average 1989 - 1993

GROUNDWATER TRACKING PARTICLE TRACE LEGEND

Contamination Extent From 1993 Well Evaluation Report

Complete 10 Year Particle Track

Final Particle Position in Stream at or Before 10 Years

Particle Captured by Drain or Trapped at Cell at or Before 10 Years

Number of Tracking Steps Exceeded

Possible Future Monitoring Site

ALL RESULTS REPRESENT UNRETARDED GROUNDWATER FLOW

Existing Alluvial Monitoring Well

Surface Water Feature

Subsurface Drain

Extent of Rocky Flats Alluvium

Unsaturated Area

TN

0° 11'

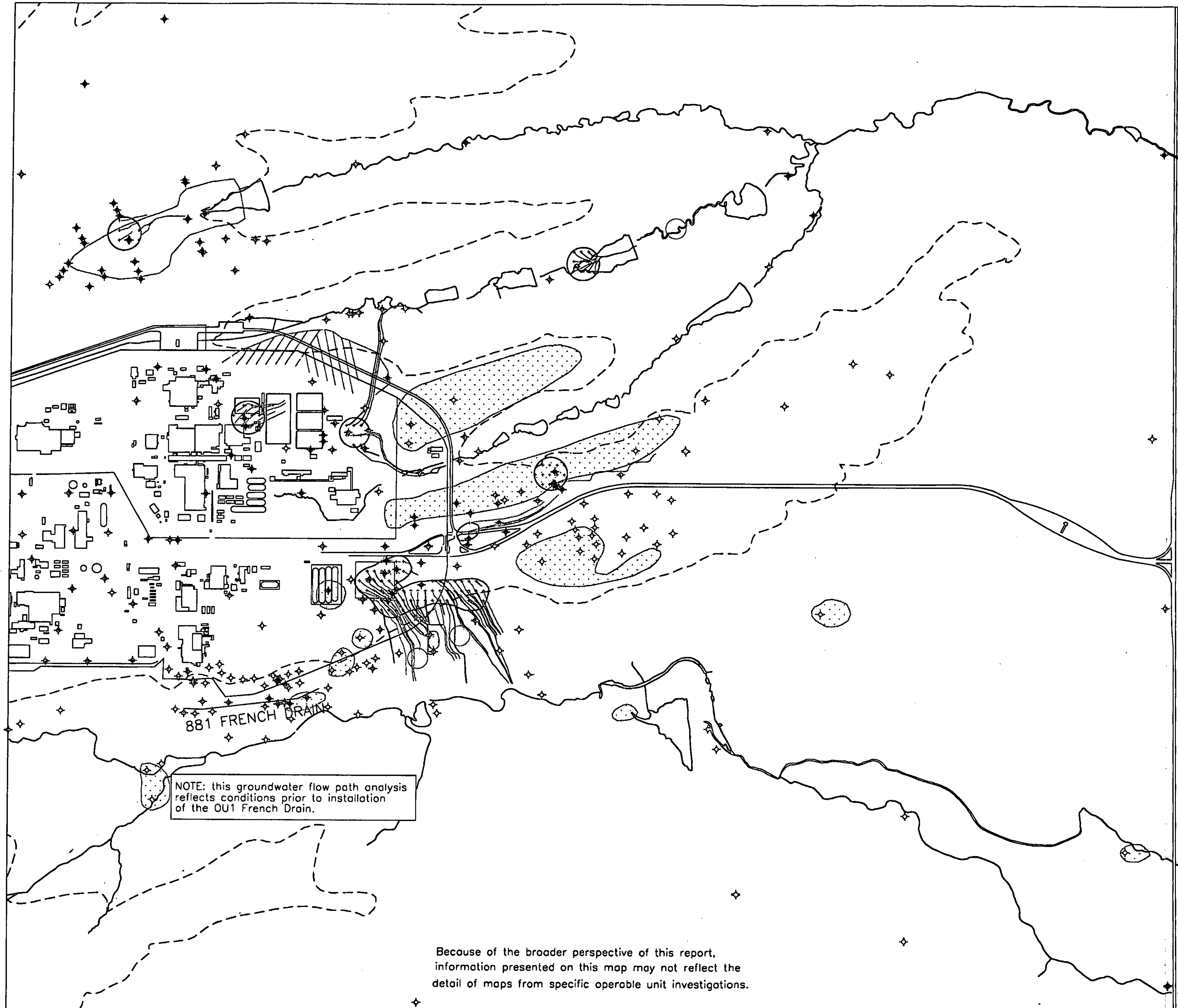
500 0 1000 2000

FEET

State Plane Coordinate Projection

1994 Well Evaluation Report
Figure 7-16

Date: March 1995



U.S. Department of Energy

Rocky Flats

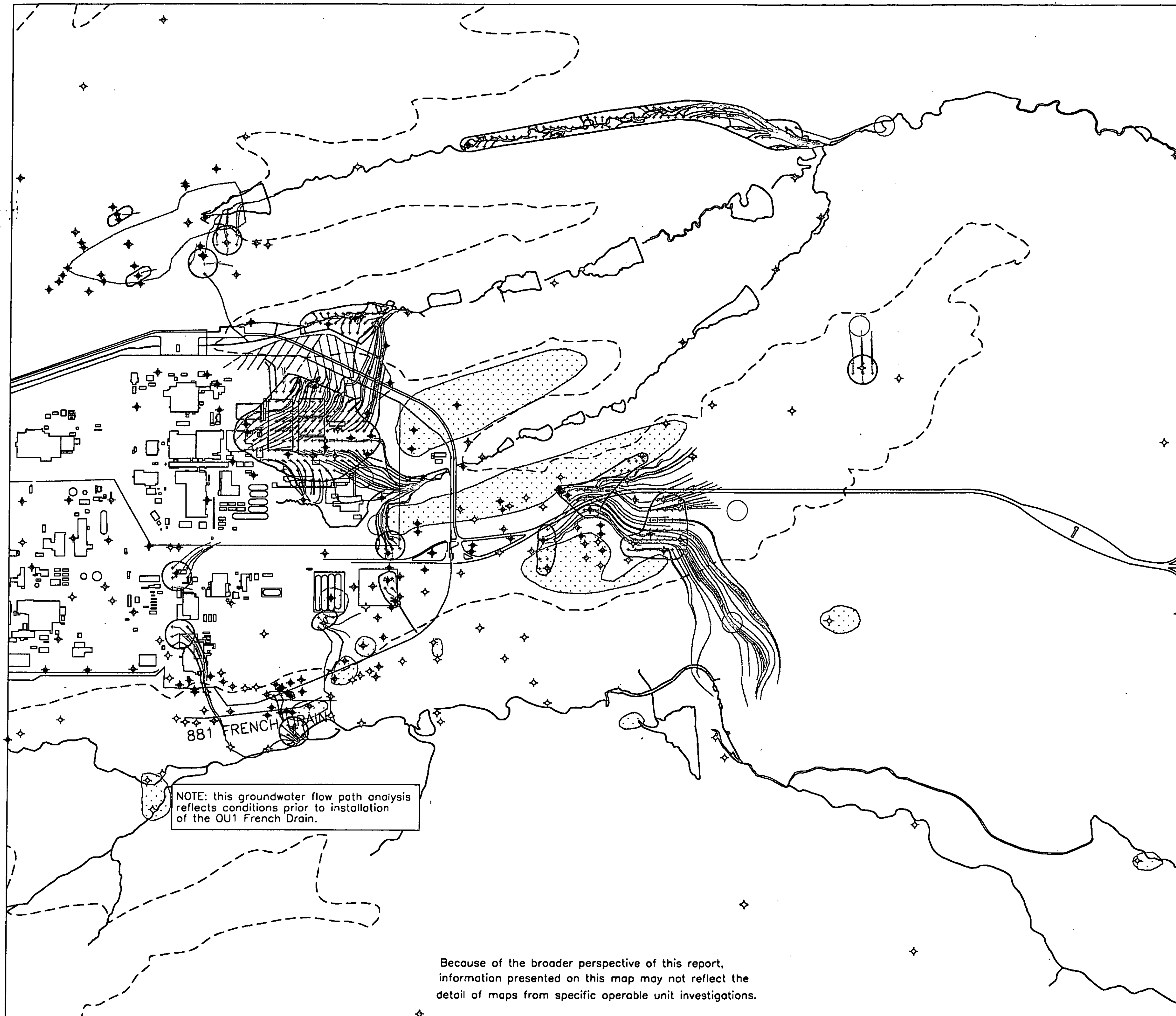
Environmental Technology Site

Americium-241 2nd Quarter 1992

1994 Well Evaluation Report

Figure 7-15

Date: March 1995



U.S. Department of Energy

Rocky Flats

Environmental Technology Site

Nitrate plus Nitrite
2nd Quarter 1992

GROUNDWATER TRACKING PARTICLE TRACE LEGEND

Contamination Extent From 1993 Well Evaluation Report

Complete 10 Year Particle Track

Final Particle Position in Stream at or Before 10 Years

Particle Captured by Drain or Trapped at Cell at or Before 10 Years

Number of Tracking Steps Exceeded

Possible Future Monitoring Site

ALL RESULTS REPRESENT UNRETARDED GROUNDWATER FLOW

Existing Alluvial Monitoring Well

Surface Water Feature

Subsurface Drain

Extent of Rocky Flats Alluvium

Unsaturated Area

TN

0° 11'

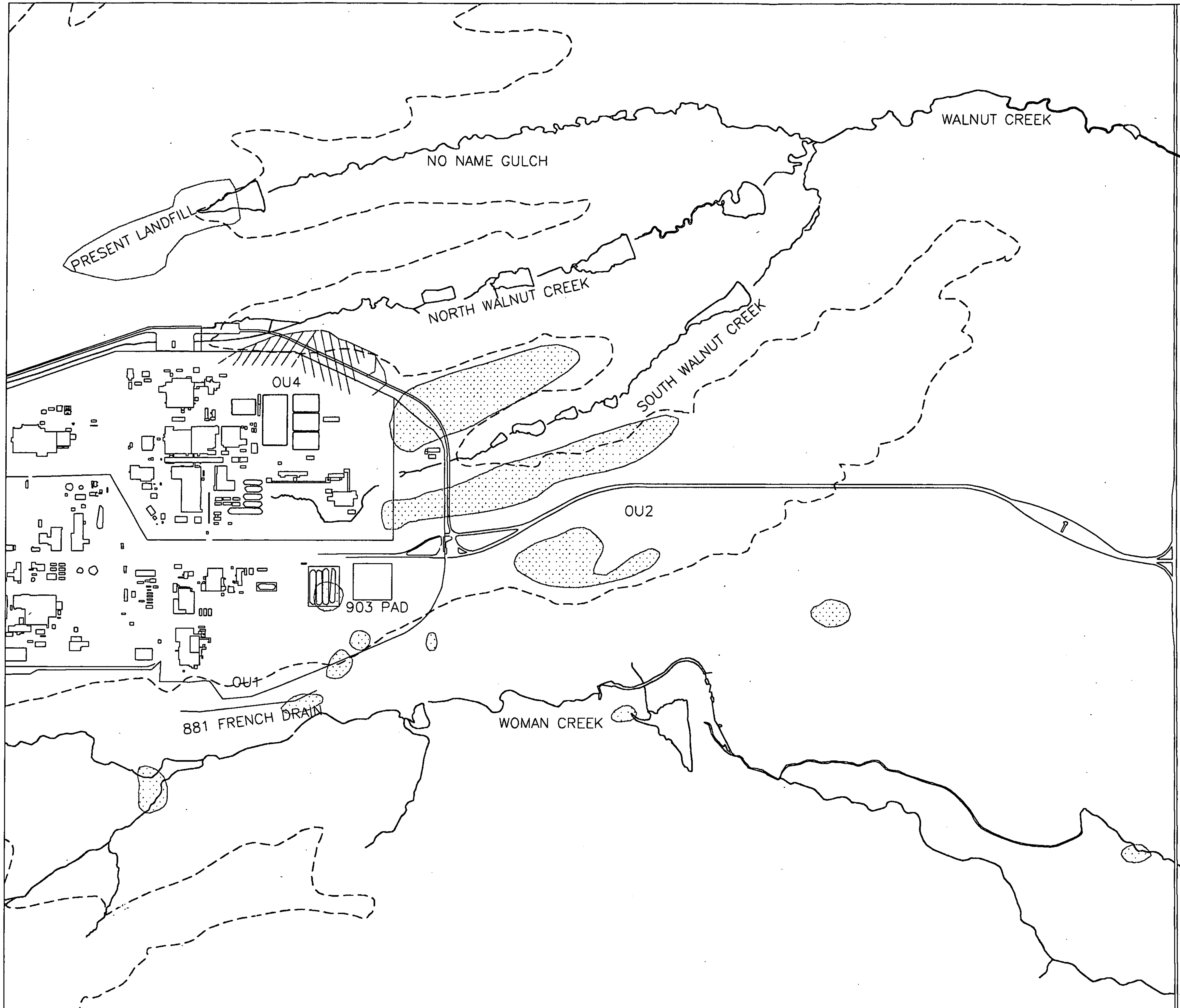
500 0 1000 2000

FEET

State Plane Coordinate Projection

1994 Well Evaluation Report
Figure 7-14

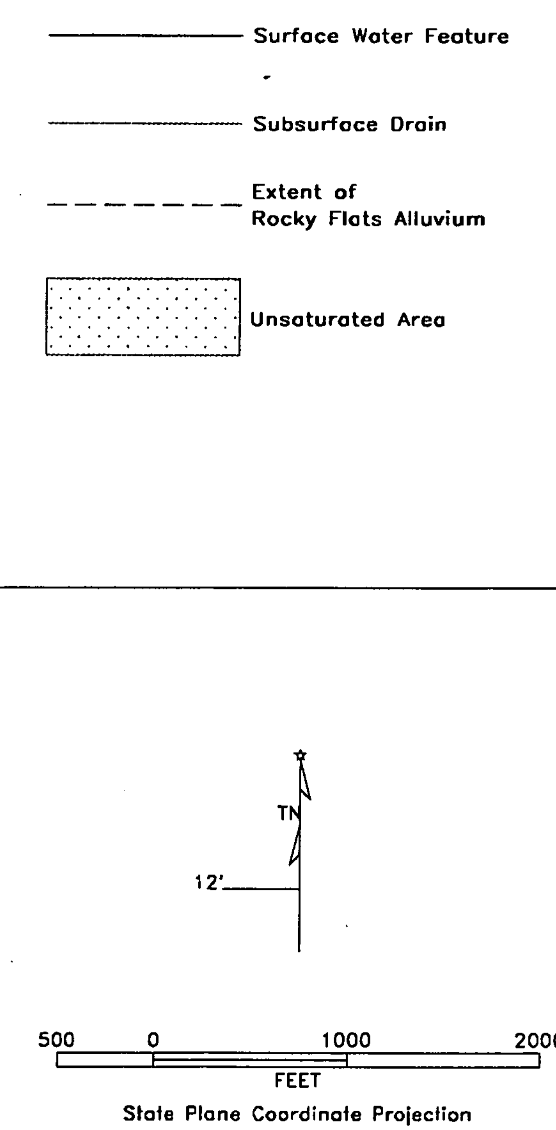
Date: March 1995



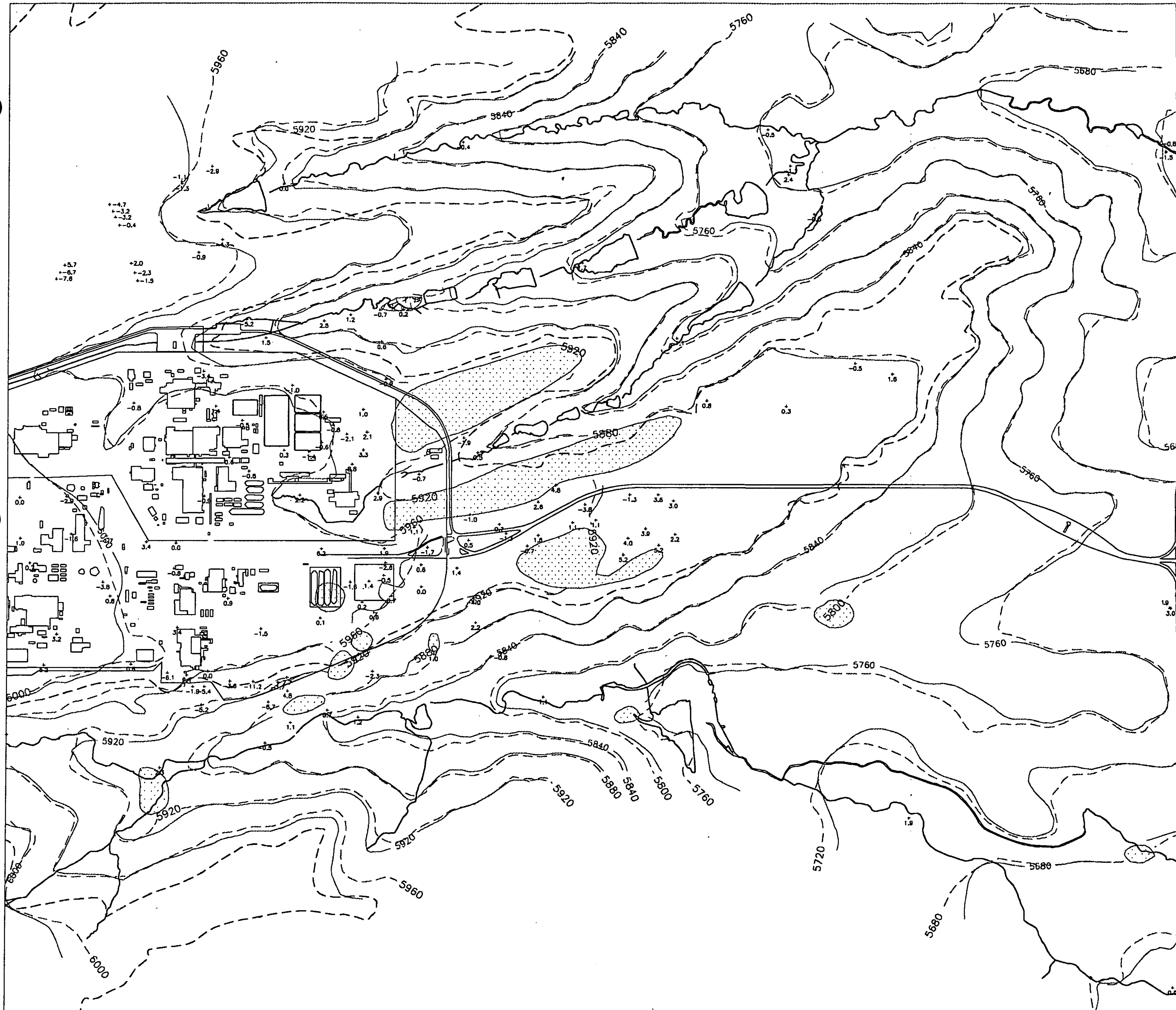
U.S. Department of Energy
Rocky Flats
Environmental Technology Site

Location Map

LEGEND



1994 Well Evaluation Report
Figure 7-13
Date: March 1995



U.S. Department of Energy

Rocky Flats

Environmental Technology Site

Simulated and Observed Groundwater Elevations

LEGEND

Contour Based on Observed Groundwater Elevations

Contour Based on Flow Model Results

Contour Interval 40 feet

3.0 Calibration Error

Surface Water Feature

Extent of Rocky Flats Alluvium

Desaturated Area

TN

12'

500 0 1000 2000

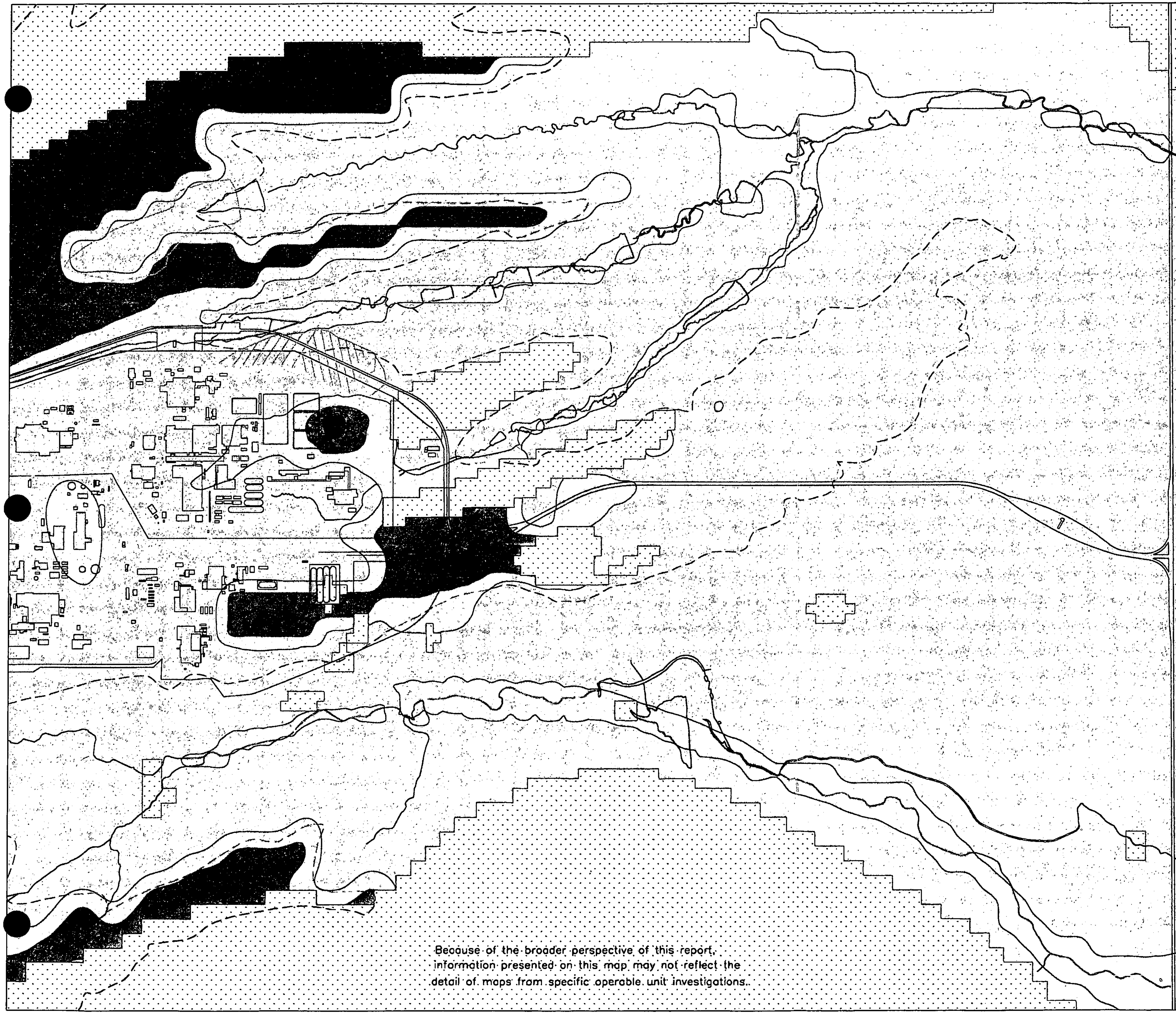
FEET

State Plane Coordinate Projection

1994 Well Evaluation Report

Figure 7-11

Date: March 1995



U.S. Department of Energy
Rocky Flats
Environmental Technology Site

Flow Model Recharge Values (ft/day)

LEGEND

Surface Water Feature

Subsurface Drain

Extent of Rocky Flats Alluvium

0.00015

0.0001

5e-05

No Flow Cells

TN

0° 11'

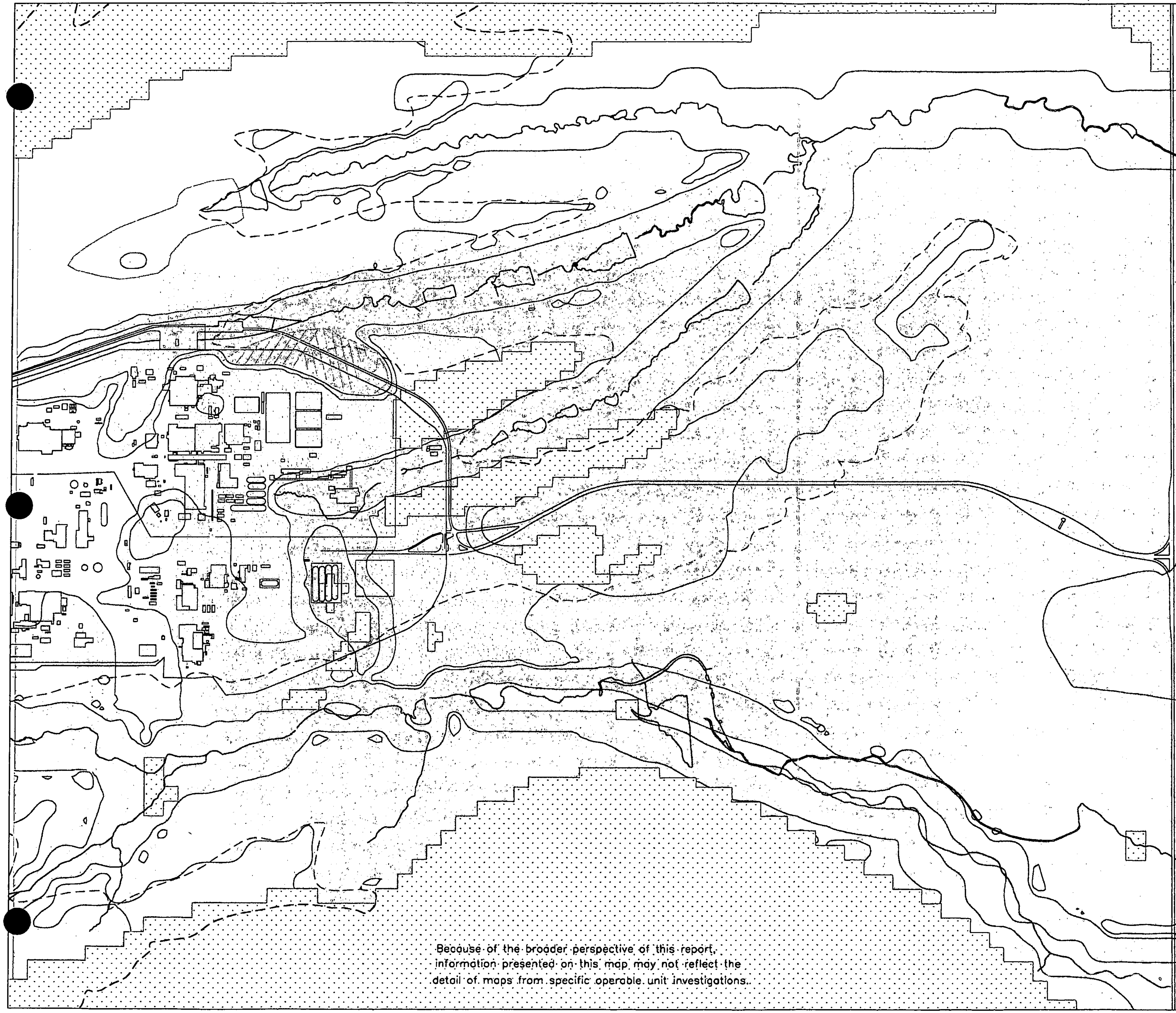
500 0 1000 2000

FEET

State Plane Coordinate Projection

1994 Well Evaluation Report
Figure 7-10

Date: March 1995



U.S. Department of Energy

Rocky Flats

Environmental Technology Site

Flow Model Values for Hydraulic Conductivity (ft/day)

LEGEND

Surface Water Feature

Subsurface Drain

Extent of Rocky Flats Alluvium

10

1

0.5

No Flow Cells

TN

0° 11'

500 0 1000 2000

FEET

State Plane Coordinate Projection

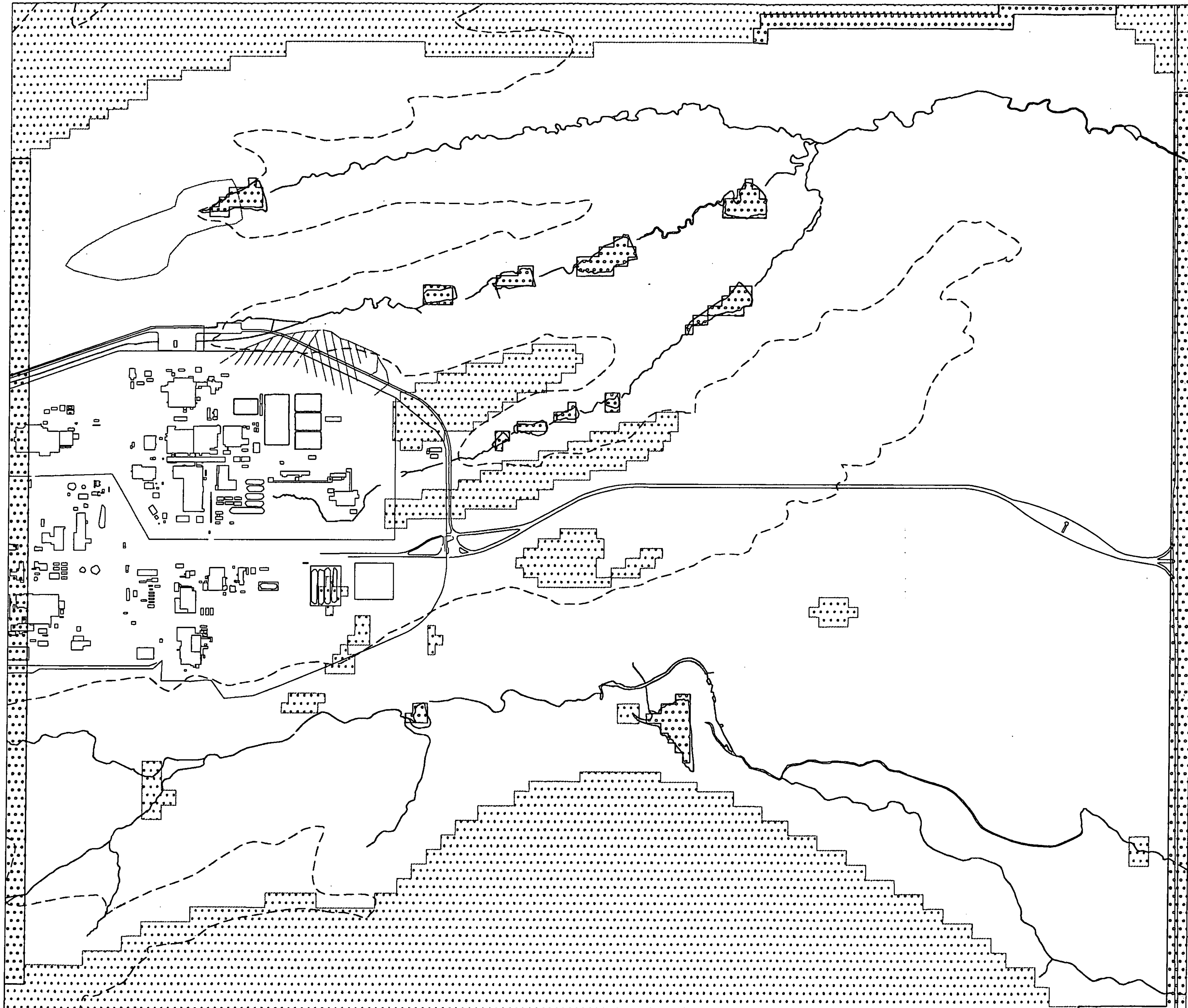
1994 Well Evaluation Report

Figure 7-9

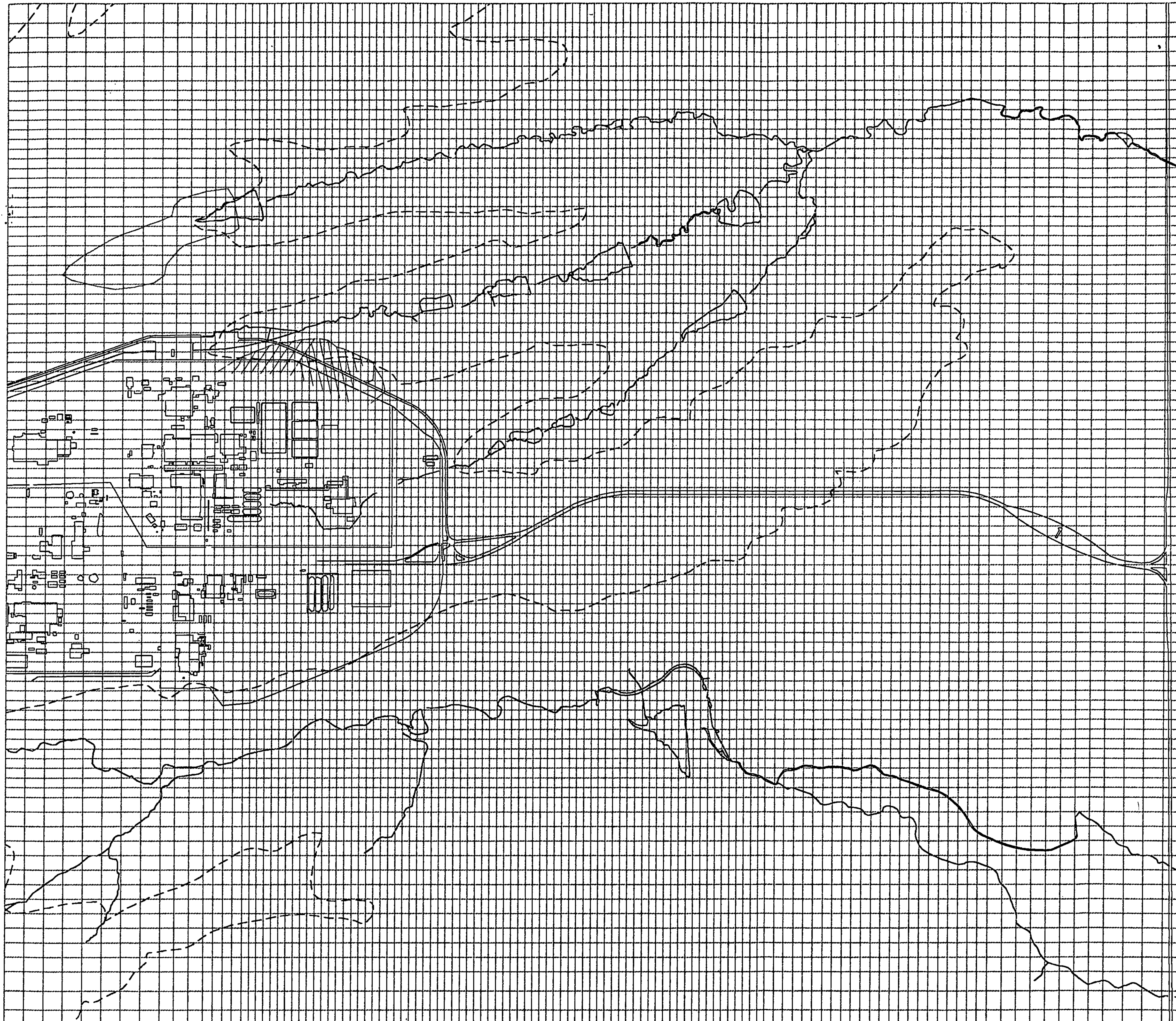
Date: March 1995

U.S. Department of Energy
Rocky Flats
Environmental Technology Site

Flow Model Boundary Conditions



1994 Well Evaluation Report
Figure 7-8.
Date: March 1995

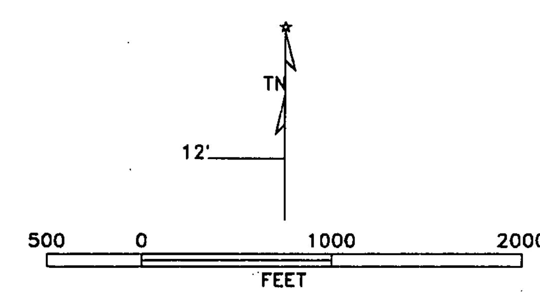


U.S. Department of Energy
Rocky Flats
Environmental Technology Site

Flow Model Grid Configuration

LEGEND

Surface Water Feature
Subsurface Drain
Extent of Rocky Flats Alluvium
MODFLOW Grid

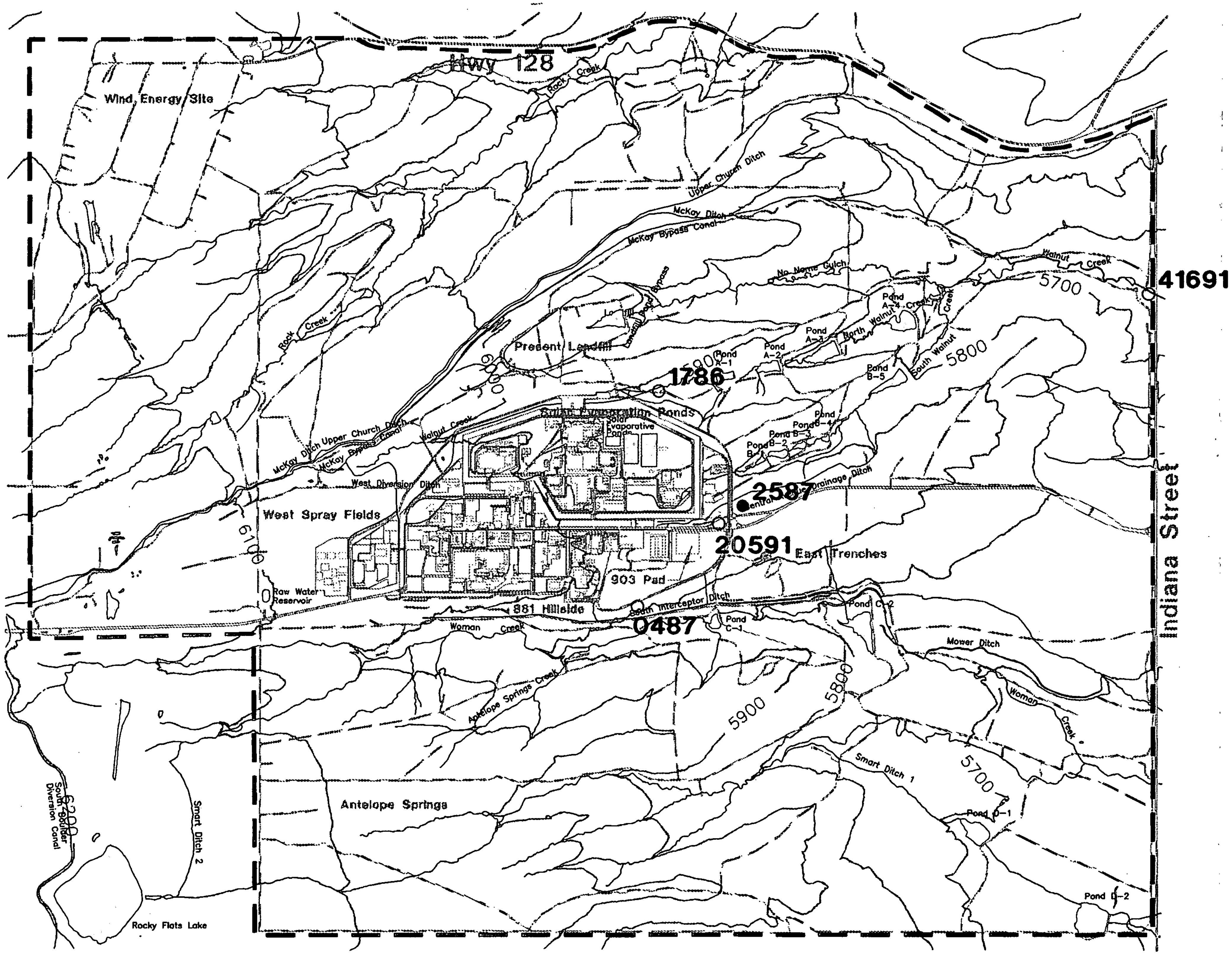


State Plane Coordinate Projection

1994 Well Evaluation Report

Figure 7-2.

Date: March 1995



○ 1786 ALLUVIAL WELLS

● 2587 BEDROCK WELLS

N

0 1000 2000 4000

EG&G ROCKY FLATS

Rocky Flats Environmental Technology Site, Golden Colorado

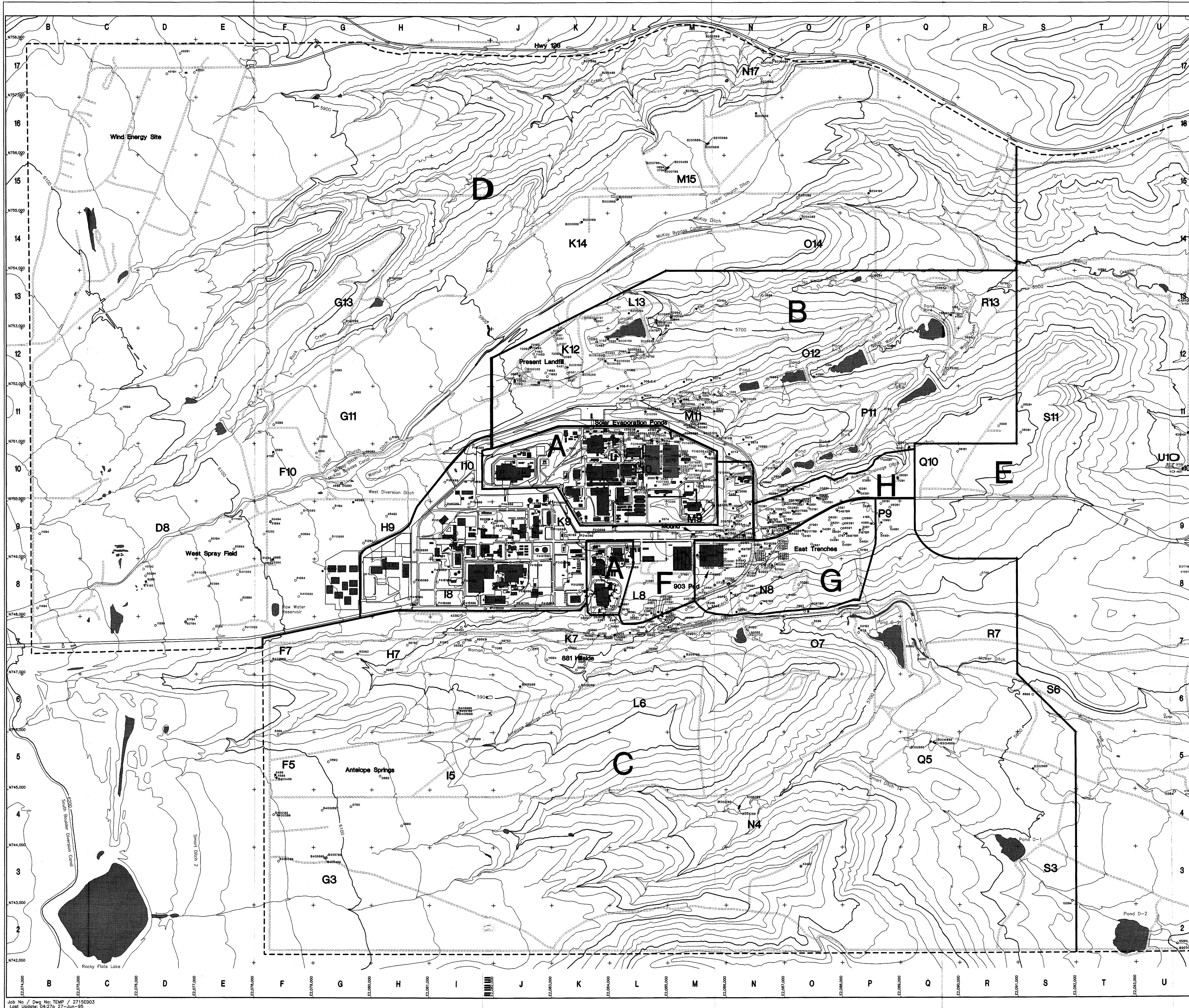
LOCATION OF WELLS

FOR FIELD METHODS

EVALUATION

1994 WELL EVALUATION REPORT

DATE : MARCH 1995 | FIGURE : 3-1



U.S. Department of Energy

Rocky Flats Environmental Technology Site

Groundwater Monitoring Well & Piezometer Location Map

(posted as of May 1994)

- Paved roads
- Unimproved dirt roads
- Streams, Ditches, and other drainage features
- Rocky Flats Environmental Technology Site boundary
- Ponds/Lakes
- Buildings or Structures
- RCRA Alluvial well
- RCRA Bedrock well
- RCRA Characterization wells
- CERCLA Alluvial wells
- CERCLA Bedrock wells
- CERCLA Alluvial/Bedrock wells
- Background Alluvial wells
- Background Bedrock wells
- Boundary Alluvial wells
- Boundary Bedrock wells
- Boundary Alluvial/Bedrock wells
- Special Purpose Alluvial wells
- Special Purpose Bedrock wells
- Special Purpose Alluvial/Bedrock wells

N

Mapscale = 1 : 6000
1 inch = 500 feet

500 0 1000 2000

State Plane Coordinate Projection
Zone 3476

Prepared By:

EG&G ROCKY FLATS

Rocky Flats Environmental Technology Site
P.O. Box 464
Golden Colorado 80402-0464
SW-A-002123

Date: MARCH 1995

Figure 1-2

REV.	DATE	DESCRIPTION	DR. BY	APP. BY
1	11/17/94	ADDED 4xx94 AND 6xx94 WELLS	RLB	LC